bookboon.com

Measurements of Body Composition by Bioimpedance

Michel Jaffrin

Michel Jaffrin

Measurements of Body Composition by Bioimpedance

Measurements of Body Composition by Bioimpedance
1st edition

ISBN 978-87-403-1254-6

Contents

1 Introduction

1.1 Body fluids

This book presents the principles of fat-free-mass (FFM), body fat (FM), and total body water (TBW) measurements. There are two body fluids compartments, extracellular water (ECW) and intracellular water (ICW) and their sum constitutes TBW which amounts in average to 73.2% of body weight (W). The ECW includes blood plasma containing proteins and red cells, about 4.5% of body weight, interstitial fluid is 16%, and lymph 2%. Interstitial water represents the difference between ECW and plasma water. The major cation of ECW plasma is sodium (142 mEq/L) and major anions are Cl, HCO_3 and proteins The ICW represents the fluid content of all body cells and constitutes 30 to 40% of body weight. It is equal to the difference between TBW and ECW. TBW volume can be measured by injecting deuterium (D_2O) in tissues as isotonic saline water. The major ion of ICW is potassium (K) with a concentration of 160mEq/L. The measurement of ECW is less precise than that of TBW, and that of ICW is made by the difference between TBW and ECW.

1.2 Fat mass and fat-free mass

The measurement of body composition such as fat-free mass (FFM) or lean body mass, bone mineral content (BMC), and body weight is important in clinical nutrition, as overweight and obesity are recurrent problems in developed countries, which may lead to various diseases such as diabetes, cancers and cardiovascular anomalies [1]. The lean body mass (LBM) consists of 15% of bones with a density of 1.56, 10% of structural lipid with a density of 0.94 and 75% of cells with a density of 1.06. Other important parameters are accessible from the five listed, as fat mass (FM) is equal to W-FFM, the lean body mass is given by FFM-BMC (See **Fig. 1).**

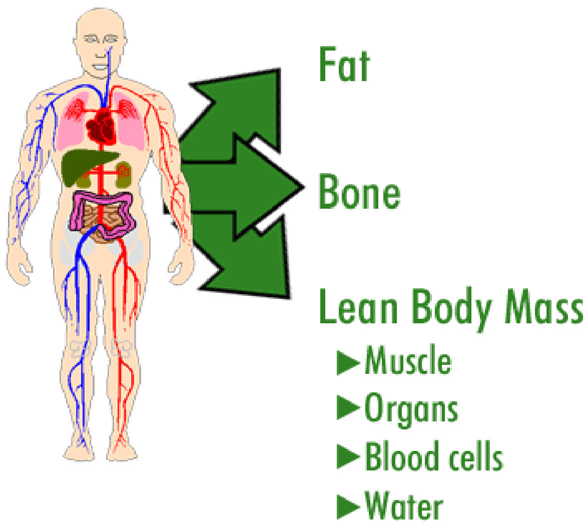

Fig. 1. Body composition: Fat mass, bone mineral content and fat-free- mass containing BMC, muscle mass, extra and intra cellular water.

It is thus important for this population to adapt their food intake and exercise. These measurements can be made using Dual X-Ray absorptiometry (DXA) shown in **Fig. 2** which calculates independently FFM, FM and BMC for the whole body and give a detailed distribution of these tissues inside the body. But DXA measurements are expensive and cannot be repeated frequently, due to radiation.

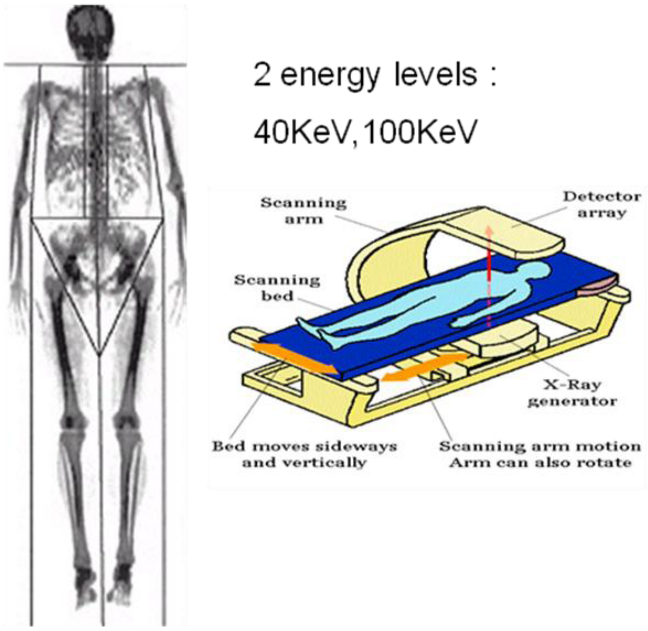

Fig. 2 Dual X-Ray Absorptiometry

1.3 Bioimpedance techniques

Bioimpedance is a simple method permitting to measure FFM as these tissues are electrically conductive due to ions contained in body fluids, while FM is not conductive. Measurements of tissue resistances R were initially made in supine position with medical impedance meters using four non reusable adhesive electrodes and were not invasive. The normal procedure was to place one current electrode on the right hand, a voltage electrode on the right wrist, a distal current electrode on the right foot and a voltage electrode on the right ankle at about 6 cm from current electrodes. The right side was selected to avoid the current to pass through the heart. A large variety of medical impedance meters is now available and several have multi-frequency electronics, in order to measure both ECW from the resistance at low frequency (5 kHz) and TBW from the resistance at high frequency (50 kHz or more). A good example is the Xitron Hydra 4200 (Xitron Technology, San Diego, USA) which operates at 50 frequencies from 5 to 1000 kHz and permit bioimpedance spectroscopy (BIS) and uses standard rectangular electrodes 1 cm wide and 8 cm long. It is calibrated by a phantom. Since actual DXA are considered as reference measurements for FFM, the comparison with DXA data permits to obtain equations giving FFM as function of resistance, body height, weight, sex and, in some cases, age. The body weight is measured by a body scale and subject height by a wall mounted scale. But this method is empirical and may not be accurate in subjects with abnormal morphology.

The body resistance measured is the sum of right arm and right leg resistances, plus the trunk longitudinal resistance. Bioimpedance analysis (BIA) devices use a 50 kHz frequency, while impedance meters measuring resistance of body fluids use several frequencies from 5 kHz to 1 MHz to measure independently ECW(at low frequency) and TBW (at high frequency) [2]. The advantages of these impedance meters are that their electrodes have a standardized shape and area and are placed at well defined positions. BIA devices can use equations from the literature obtained at 50 kHz [3]. Their drawbacks are that they are expensive and their measurements take about 10–15 min for placing electrodes and waiting for fluid equilibrium in supine position.

An important innovation in 1996 was the development of foot-to-foot impedance meters (FFI) consisting in a body scale equipped with two current and two voltage reusable metal electrodes and a software to determine FFM or FM from the same parameters as medical devices. Measurements, taken in standing position, are faster than with medical devices and benefit from body weight supplied by the scale. Main companies are Tanita (Tokyo, Japan) and, in France, Tefal (SEB, Rumilly). Due to their large diffusion in the general public, their prices were low, between 70 and 110 €.They are powered by1.4 V batteries delivering generally a 0.8 mA current. Body resistance measured by FFI is smaller than that measured in supine position by a medical impedance meter as leg resistance is lower than that of arms. In standing position, fluid accumulates in the calves and forearms due to gravity, decreasing limb resistance.FFI only measure the resistance of the lower body, consisting in both legs and waist width, representing one-third of the body, while the trunk represents half the body and only 20% of the total body resistance. But, with appropriate software, they can be at least as accurate as medical impedance meters, since they avoid the variability of arm resistances.

Another interesting event was the introduction in 2003 of eight electrodes impedance meters, such as the Tanita BC 418, consisting in a FFI to which two current and two voltage electrodes, connected by electrical cables, have been added for the hands. It can measure automatically the resistance of five current lines connecting hands and feet and extract the resistance of each limb and the trunk by solving a system of five equations. Of course, it measures also whole body resistance, FFM and FM. Two Korean companies commercialize multi-frequency eight-electrodes FFI, the InBody 720 (Biospace, Seoul) and the X- Scan (Jawon, Kyungson). Hand electrodes are mounted on a horizontal rod fixed to a vertical column together with a screen to display body composition data. These professional devices are, of course, much more expensive than normal FFI, but Tanita Co commercializes several models of eight-electrodes devices, which cost between 200 and 300€.

2 Various types of impedance meters

2.1 Description of medical impedance meters with adhesive electrodes

The multi-frequency XITRON Hydra 4200, shown in **Fig. 3**, operates at at 50 frequencies from 5 to 1000 kHz with a current of 0.7 mA and calculates resistances at zero and infinite frequencies by extrapolation, for measuring respectively ECW and TBW. The BodyExplorer of Juwell Medical (Gauting, Munich) 50 kHz, the multi-frequency Z-Metrix from Bioparhom, the Bio-ZMII from from Nutrilog (France) and the BODYSTAT 1500, 50 kHz from Isle of Man are also shown in Fig. 3. Adhesive electrodes for Xitron 4200 for measuring hand-to-foot resistances are shown in **Fig. 4**.

Bodystat

Xitron 4200

Z Metrix

BodyExplorer

Fig. 3. 50 kHz Bodystat impedancemeter, multifrequency XITRON 4200, Z-Metrix (Bioparhom) and BodyExplorer (Jewell Medical)

Fig. 4 Adhesive electrodes for XITRON 4200 on hand and foot

The BCM impedance meter of Fresenius Medical Care (Bad Homburg, Germany), shares the Xitron electronics and is used for monitoring body fluids volumes during hemodialysis.

The RJL (Clinton, Missouri) is available in five models: Quantum II, X, III, IV and Desktop (with eight electrodes).

Biodynamic (Biodyn Corp)sells a BIA 310 50 kHz impedance meter.

2.2 Description of four electrodes FFI

The recent TanitaBC 730 has four circular electrodes and costs 60 €. The Tefal Bodymaster, and BodySignal, the Terraillon Fitness from France and the Withings are shown in **Fig. 5**. The Tefal BodyMaster Vision and the Tefal BodySignal have both square signals of 114 kHz (see **Fig. 6**). The Terraillon costs only 35 €.

Fig. 5. FFI Tefal Bodymaster, BodySignal,Withings and Terraillon

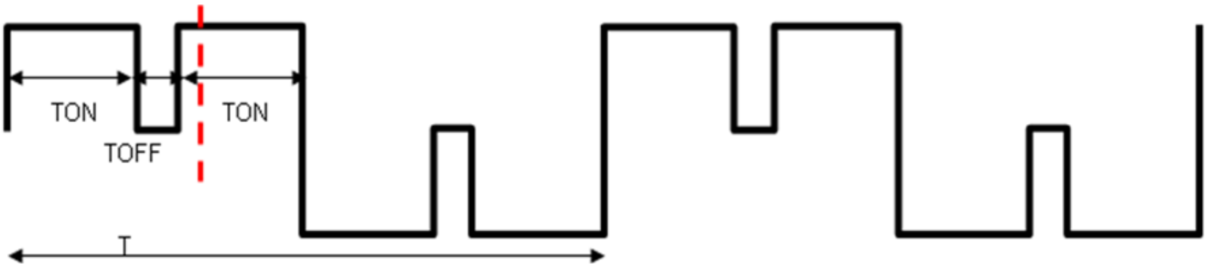

Fig. 6. Schematic of square wave signal of Tefal electronics

2.3 Description of eight-electrodes impedance meters

The Omron HBF 511, is equipped with 4 electrodes for the hands in addition to plantar electrodes and costs 100€.

The Tanita BC 545 N costs 239€, and the Tanita BC 601, shown in **Fig. 7**, costs 219 €.

Fig. 7. Eight electrodes FFI, Tanita BC 601 and BC 545 N

Jawon Co, Kyungson, Korea manufactures the X- Scan medical multi-frequency (1-1000 kHz) shown in **Fig. 8** and another one Genius 220. Another Korean company, Biospace manufactures two multi-frequency impedance meters, the InBody 320.and the 720.

Fig. 8. X-Scan Medical eight electrode impedance meter (Jawon, Kyungson, Korea)

3 Applications of impedance meters

These applications are described with a review of the relevant literature.

3.1 Medical Impedance Meters

Rush et al [4] used a 50 kHz BIM4 Impedimed (Capalaba, Australia) with self-adhesive electrodes on Asian and Fijian Indians (110 men and 101 women) and developed a prediction equation for FFM based on BIA measurements. People who were diabetic, pregnant or taking medication affecting weight were excluded. They compared their FFM data with those of a GE Lunar DXA (Madison, WI, USA) by Student T-test, using nine equations from the BIA literature. They provided mean +SD data for men and women, but they also separated subjects data in 5 columns by age 20–29 yr, 30–39, 40–49, 50–59 and 60+. Rush et al proposed two new BIA equations for FFM prediction, suited for male and female Asian Indian population. For 110 males, the equation was

$$FFM = 0.382\ H^2/R + 0.167W + 0.320H - 33.382 \tag{1a}$$

where H is the height in cm, R the body resistance in ohm, and W the weight in kg. The correlation coefficient was $R^2=0.84$. Predicted mean FFM was 50.50±6.38 kg, against a DXA FFM of 50.44 ±3.38 kg and p value of T test was 0.52.

For 101 females, it was

$$FFM = 0.456H^2/R + 0.127W + 0.0746X + 5.959 \tag{1b}$$

where X is the reactance and $R^2= 0.70$. Detailed data are given in **Table 1**. P-values of Student T-test indicate whether differences are significant when $p< 0.05$ and not significant if $p>0.05$. A p-value of 0.68 indicates that differences are very small. Minimum bias was -0.42 kg with Bhat et al equation [5] in validation group for males

$$FFM= 0.287H^2/Z + 0.364W + 12.97 \tag{2a}$$

Men	All:110	N=22	N=31	N=21	N=23	N=13	P-value
Age,yr	19-74	19-29	30-39	40-49	50-59	60-74	
Height,cm	170±6.9	173±6.0	170±8.0	170±5.6	167±6.1	167±7.1	0.68
W, kg	74.±11.7	78±12.1	73±12.4	77±10.8	72±11.3	69±10.7	0.05
FFM, kg	50±6.9	54±6.2	50±7.9	51±5.8	49±5.8	47.5±8.2	0.59
FM kg % BF	23±7.8 31±6.8	24±8.5 30±6.9	24±8.3 32±7.5	25±7.5 32±6.3	23±8.2 31±7.2	22±4.5 30±4.7	0.52 0.65
Women	All 101	N=16	N=25	N=28	N=17	N=15	
Height,cm	156±5.7	159±5.3	159±5.3	157±5.3	154±5.0	153±6.2	0.011
W, kg	65 ±10.2	58.9±6.6	68±11.3	65±10.7	67±11.1	66±9.6	0.062
FFM, kg	36±3.6	34.4±2.0	37.3±3.4	36.3±4.6	36.9±4.5	35.1±3.6	0.083
FM kg % BF	28.0±8.4 42.9±6.8	23.3±6.5 39.8±6.9	29.9±9.7 43.4±7.7	28.2±8.4 43.0±7.1	28.9±8.3 43.3±6.1	29.4±9.4 45.1±5.0	0.14 0.28

Table 1. Characteristics of male and female Asian Indians grouped by decade of age. From Rush et al [4]

It gave a mean FFM prediction of 50.0 ± 5.6 kg with a p-value of 0.22, which was close to DXA value of 50.18, very close to that of DXA. And for females, the minimum bias was 0.53 kg using Duremberg equation [6] in validation group.

$$FFM= 0.34H^2/R +0.1534H+0.273W -0.127 \text{ Age}+ 4.56 \text{ sex} -12.44 \quad (2b)$$

The mean prediction was 35.73 ± 34 kg against a DXA value of 35.22 ± 2.79 kg and a p-value of 0.08, worse than for males.

Predicted mean FFM in women was 36.05 ± 3.0 kg versus 36.04 ± 3.60 kg by DXA and p= 0.33. The male equation was more accurate than the female one as its value of p was higher. The good results of Eqs 1a and 1b are due to the fact the entire cohorts were used to determine these equations. It is remarkable that BIA equations gave very close data for mean FFM and FM with DXA data for both men and women, although Asian Indians have higher body fat than Caucasian subjects. Only four of 101 women had %BF less than 30% and 17 men had %BF less than 25%. This is due to specific equations developed by the authors.

3.1.1 Measurements of body fluid volumes

Jaffrin et al [7] evaluated the potential of a Tefal BodyMaster FFI to measure ECW, FFM and FM by-comparison with a multi-frequency Xitron Hydra 4200 on 60 volunteers (30 men and 30 women) aged from 18 to 71 yrs. The use of multi-frequency and the conductivity theory of Hanai [8] in bioimpedance spectroscopy (BIS) permit a more precise calculation of TBW and therefore of FFM since the two parameters are connected. However, it is clear that the same equations for ECW and FFM cannot be used with both impedance meters as the XITRON measures the wrist-ankle resistance in supine position and the Tefal, the foot-to-foot one in standing position. Therefore the authors choose a Hologic QDR Delphi DXA as a reference method. Subjects undressed and wore a light gown. After standing during 12 min to avoid fluid shifts due to change in posture, TBW was measured by the Xitron and FFM was calculated as TBW/0.732. Mean FFM differences between Tefal and DXA data were 1.57 ± 3.09 kg for men and -0.08 ± 2.98 kg for women. Mean differences between Xitron–measured and DXA-measured were 0.21 ± 3.03 kg for men and 0.15 ± 2.40 for women indicating a slight overestimation by the Xitron. Details are shown in **Table 2**. Concerning the measurement of ECW by the Tefal, **Table 3** lists the extracellular resistance measured by Tefal Re_t and the resistances measured by the Xitron Re_{ff}. Equations for extracellular volume Ve were, for the Xitron.

	Men, n=27	Women, n=30
$\rho\infty_{ni}$ from DXA, Ω cm	104.31 ± 7.9	100.5 ± 7.8
$\rho\infty_{mi}$ Matthie, Ω cm	98.0 ± 5.2	90.1 ± 4.0

Table 2. Mean and SD of individual TBW resistivity of 57 subjects calculated by different methods

electrolyte	Na^+	K^+	Ca^{2+}	Mg^+	Cl^-	HCO_3^-	PO_4^-	protein	Org acid
plasma	142	4	5	3	103	27	2	16	5
Interstitial	151	4.3	5.4	3.2	109.7	28.7	2.1	17	5.3
ICW Muscle	10	160		35	2	8	140	55	

Table 3. Ion concentrations in mEq/L of ECW (plasma + interstitial) and ICW of muscle cells. Adapted from Deuremberg et al [6]

$$Ve = k_e\ (H^2W^{0.5}/Re)^{2/3} \tag{3a}$$

And for the Tefal

$$Ve_t = k_t\ (H^2W^{0.5}/Re_t)^{2/3} \tag{3b}$$

The low frequency resistance Re_t of the Tefal was not significantly different (8.5 ± 31 Ω) from the ECW resistance Re measured by the Xitron (Eq. 3a) with the same electrode position, under the feet. The difference between Ve and Ve_t was only -0.09 ± 0.66 L. Mean values and SD of Xitron and Tefal resistances, and Tefal and Xitron ECW shown in Table 3 are close.

Jaffrin and Moreno [9] measured TBW in a group of 56 healthy volunteers (29 women and 27 men) using a Tefal BodyMaster FFI which has been modified to provide in addition the ECW and TBW resistances to measure these volumes and a Xitron Hydra 4200. TBW was treated as a single fluid macroscopically homogeneous although it was not the case, with a mean resistivity $\rho_\propto$. The method was transposed from the BIS method of Mathie [10]. The TBW volume V_{tn} was given by

$$V_{tn} = K_x(H^2W^{0.5}/R_\propto)^{2/3} \tag{4a}$$

where R∝ was the resistance measured by the Xitron at 1000 kHz and H is the height in cm. The coefficient K_x is given by

$$K_x = 10^{-2}\,(4.3\rho_\propto)^{2/3}\,D_b^{1/3} \tag{4b}$$

where D_b is the body density equal to 1.05 kgL^{-1}. The mean TBW resistivity determined from DXA measurements was 104.3 $\Omega\ cm^{-1}$ for men and 100.5 $\Omega\ cm^{-1}$ for women (**Table 4**), while ion concentrations of ECW and ICW of muscle cells are listed in **Table 5**. Thus Eq (4b) gives K_x = 0.576 for men and 0561 for women with selected units. Eq. 4a has been applied to the Tefal, but with a different coefficient K_t since its resistance R_{hf} is different from R∝ as it is measured at a lower frequency with plantar electrodes instead of adhesive wrist–ankles ones. To determine K_t we calculated for each subject an individual coefficient K_i for the Tefal from

$$V_{tn} = K_i(H^2W^{0.5}/R_{hf})^{2/3} \tag{5a}$$

		Men, n=30		Women, n=30	
		Mean	SD	Mean	SD
FFM,kg	DXA	60.67	7.36	43.09	4.22
	Tefal	62.24	6.61	43.01	3.56
	Xitron	60.88	8.66	43.24	5.24
FM, kg	DXA	15.07	8.73	19.57	7.0
	Tefal	13.1	8.40	19.6	6.1
	Xitron	14.81	8.02	19.36	6.0
BMC	DXA	2.81	0.45	2.25	0.27

Table 4. Comparison of FFM and FM measured by DXA, Tefal and Xitron impedance meters. Adapted from Jaffrin et al [7]

		Men, n=30		Women, n=30	
		Mean	SD	Mean	SD
Re_t ,Ω	Tefal	563	73.0	617	69.0
Re_{ff} ,Ω	Xitron	568	70.0	628	71.0
Ve_t , L	Tefal	17.84	2.28	13.02	1.35
Ve, L	Xitron	17.93	2.53	13.04	1.44
Ve_t/Ve		1.002	0.046	1.001	0.038

Table 5. Comparison of extracellular resistances and volumes measured by Tefal FFI and Xitron. Adapted from Jaffrin et al [7]

Eq.5a assumes that the TBW volume calculated from R_{hf} is equal to the volume measured by the Xitron and K will be determined as the averages values of K_i for men and women separately. Thus TBW volumes measured by Tefal V_{tt} will be given by

$$V_{tt} = K_t \, (H^2 W^{0.5}/R_{hf})^{2/3} \qquad (5b)$$

Comparison of Tefal and Xitron resistances, FFMand TBW volumes are given in **Table 6.** P-values for differences were 0.694 for men and 0.902 for women, meaning that differences were small. The last column indicates mean differences and SD of Tefal TBW volumes and those determined by deuterium dilution V_{td} on a second Caucasian group of 91 subjects. Mean differences were -0.38 ± 2.27 L for men and 0.72 ± 2.1 L for women, larger than for differences between Tefal and Xitron, but not significant as P-values were 0.237 for men and 0.060 for women. Although the Tefal FFI and Xitron use completely different electrodes placed on different locations, different electronics and are utilized in standing position for Tefal and supine one for Xitron, it was encouraging that their TBW measurements were quite close, at least in a non-obese Caucasian population.

	R_∞ Ω Xitron	R_{hf}, Ω Tefal	FFM kg Tefal	V_{tn} L,Xitron	V_{tt} L, Tefal	V_{tt}-V_{tn} L	V_{tt}-V_{td} L
Men, N=27	411±48	489±71	59.8±7.4	44.6±5.9	44.5±7.1	0.17±2.27	-0.38±2.27
Women N=29	506±57	543±53	42.4±4.2	31.6±3.6	31.7±3.5	0.04±1.88	0.72±2.4

Table 6. Mean values and SD of Xitron and Tefal resistances,Tefal FFM, Xitron and Tefal ECW volumes and their differences. Adapted from Jaffrin and Moreno [9]

Moreno et al [11] investigated the body composition of 13 adolescent girls suffering from anorexia nervosa and 17 healthy controls of similar age group, using a Xitron 4200 and a modified Tefal BodyMaster FFI. Anorexia nervosa (AN) is an eating disorder which reduces body fat and proteins intake and affect adolescent girls aged from 10 to 18. Analysis of body composition is important in this case, as weight alone is not sensitive enough as a loss of body cell mass (BCM) including proteins and ICW may be compensated by an increase in ECW, which cannot be detected from the weight. DXA can measure FM and FFM, and has been chosen as reference but it cannot be repeated at short intervals because of cost and X-ray exposure and does not measure directly fluid volumes. Values of TBW volumes V_{tt} measured by Tefal and V_{tx} by Xitron with the new method described in [7, 10] , those of ECW volumes V_{et} measured by Tefal and V_{ex} by Xitron and ICW volumes V_{it} and V_{ix} are listed in **Table 7** for anorexic girls and for controls of same age. Differences between V_{tt} and V_{tn} for anorexic girls were not significant since p-value is 0.19, however the difference for controls is significant as p-value is <0.05. But the V_{tt} difference between anorexics and controls is not significant with p=0.14. For ECW, the difference between Tefal and Xitron data for AN is large with a p-value of 0.028, while mean V_{et} and V_{ex} are identical and controls V_{et} are not significant from anorexic. For ICW, $V_{i\ t}$ and V_{in} are not significantly different for anorexics from DXA with p = 0.14, but they are for controls. The Tefal FM values FM_t and the Xitron one FM_n also shown in Table 7 were overestimated relatively to those of DXA in anorexics, while they were close between Tefal and Xitron in controls with a p-value of 0.641. If the Tefal was in good agreement with Xitron for controls, it overestimated it in seven anorexics. This can be attributed to the presence of extracellular oedema in the legs of these subjects. The systematic FFM underestimation of AN subjects by the Tefal was probably due to their different morphology. A modification of Tefal software by introducing FMI parameter for very lean subjects could correct this discrepancy.

		AN Girls, n=13		Controls, Healthy subjects, n=17		
		Mean ± SD	P/ reference	Mean ± SD	P/ reference	P/AN-controls
TBW, L	Tefal Vtt Xitron V_{tx}	23.6±4.4 23.0± 3.9	0.19 Reference	26.2±5.2 27.0±5.7	0.049 Reference	0.140 0.032
ECW,L	Tefal V_{et} Xitron V_{ex}	10.4±1.8 9.0± 1.9	0.028 Reference	11.2±2.0 11.2±2.2	0.900 Reference	0.260 0.008
ICW, L	Tefal V_{it} Xitron V_{ix}	13.2±2.6 14.0±3.7	0.140 Reference	15.0±3.2 15.8±3.5	0.011 Reference	0.089 0.190
FFM,, kg	Tefal Xitron DXA	30.3±4.4 31.5±5.3 33.1±4.7	$4.6\ 10^{-5}$ 0.011 Reference	37.3±8.7 36.9±7.7	Reference 0.641	0.009 0.030
FM, kg	Tefal, Xitron DXA, FMd	6.4±1.5 5.2±2.5 3.6±1.5	$4.5\ 10^{-5}$ 0.011 Reference	13.6 ±5.3 14.0±6.4 na	Reference 0.641	$3.4\ 10^{-5}$ $3.3\ 10^{-5}$ na

Table 7. TBW, ECW and ICW Fluid volumes measured by Tefal V_{tt}, and new method V_{tn}, Xitron V_{tx}, V_{et} and V_{ex} , V_{it} and V_{ix} in anorexic girls and healthy subjects From Moreno et al [11]

Jaffrin and Morel [12] proposed a method for measuring TBW volume (V_t) by a modification of the bioimpedance spectroscopy method from the body resistance extrapolated at infinite frequency ($R_\propto$) using a Xitron 4200 impedance meter. Mean TBW resistivities for men and women were determined from $R_\propto$ and fat-free mass FFM_d measured by DXA in 58 healthy subjects by assuming a hydration coefficient of 73.2%. Thus TBW volume from DXA was given by $0.732FFM_d$. According to [10], $R_{\propto.}$ may be given by

$$R_{\propto.} = \rho_a K_b H^2/V_b = \rho_a K_b H^2 V_b^{0.5}/V^{3/2}_{tnm} \tag{6}$$

Where $K_b = 4.3$ and V_{tnm} is the new TBW from the new method, V_b is the body volume and

$$\rho_a = \rho_\propto (V_b/V_{tnm})^{3/2} \tag{7}$$

where $\rho_\propto$ is the resistivity at high frequency. Therefore Eqs 6 and 7 will give

$$V_{tnm} = (\rho_\propto K_b H^2 W^{0.5}/R_\propto D_b^{0.5}) \tag{8}$$

The Xitron software gave the ECW volume V_e at low frequency and V_{tx} at high frequency and the ICW volume V_{ix} by the difference between V_{tx} and V_e. Eq. 8 gave the TBW volume by the new method V_{tn}. These volumes were compared with DXA values (V_{td}) in **Table 8** for the 1st group which gives mean values and SD of TBW volumes calculated by various methods. Differences between V_{tn} (44.35±**6.**0 L), and V_{t50} (44.64±5.95) with DXA, V_{td} (44.35±5.64 L) in men were small. The same observation was made for women, as their mean volumes were 31.65 L for V_{tn}, 31.64 L forV_{t50} against 31.54 L for V_{td}. P-values for comparison V_{td} with were high, at 0.474 for V_{tn} and 0.501 for V_{t50} for men and slightly larger for women with respectively 0.709 and 0746. The validation group of 15 men and 6 women gave similar results with V_{tn} = 45.83±5.18 L and the V_{tm} calculated by Matthie was 44.46±5.75L, against V_{td} =45.87±5.28 L for men. In women, V_{tm} was closest at 29.48±5.49 L against DXA (29.59±2.65l) while V_{tn} overestimated V_{td}.

	Men, 1st group, n=27			Women, 1st group, n=30		
	Mean±SD	P/ V_{td}	P/ V_{tn}	Mean±SD	P/ V_{td}	P/ V_{tn}
V_{td}	44.35±5.64			31.54±3.09		
V_{tn}	44.63±6.0	0.474		31.65±3.58	0.709	
V_{t50}	44.64±5.95	0.501	0.969	31.64±3.42	0.746	0.837
	Men, 2nd group, n=15			Women, 2nd group, n=6		
V_{td}	45.87±5.28	NA		29.59±2.65	NA	
V_{tn}	45.83±5.18		0.958	31.53±4.74		0.17
V_{tm}	44.46±5.75	0.107		29.48±5.49		0.95

Table 8. Mean values and SD of TBW volumes measured by DXA (V_{td}), Xitron (V_{tn},) and Xitron at 50 kHz (V_{t50}) in the 1st group. From Jaffrin and Morel [12]

Jaffrin et al [13] reviewed various bioimpedance methods permitting to measure non-invasively, extracellular, intracellular and total body water (TBW) and compared BIA methods based on empirical equations of the wrist-ankle resistance at50 kHz, zero frequency for ECW, and infinite frequencies for TBW, with BIS methods which rely on an electrical model of tissues. In order to compare these methods, impedance measurements were made with a multi-frequency Xitron 4200 impedance meter on 57 healthy subjects which had undergone simultaneously a Dual X-ray absorptiometry examination (DXA), in order to estimate their TBW from their fat-free mass. ECW and TBW volumes were calculated for these subjects using the original BIS method and modifications of Matthie et al [10] and their TBW resistivity were compared and discussed (see **Table 9**). Matthie's resistivity is given by the following expression for individual TBW resistivity $\rho_{\infty mi}$ as

$$\rho_{\infty mi} = \rho_i - (\rho_i - \rho_e)\,(R_\infty / R_e)^{2/3} \tag{9}$$

where ρ_I is the ICW resistivity, ρ_e the ECW one, R_∞ is the TBW resistance and R_e the ECW one.

		Men, n=28		Women, n=30	
DXA	Vtd, L	44.44±5.56	ΔVt-Vtd	37.77±7.86	ΔVt-Vtd
New method	Vtnm, L	44.57±5.9	0.132±2.16	31.65±3.58	0.11±1.61
Xitron	Vtx, L	42.70±6.34	-1.73±2.22	29.46±3.84	-2.08±1.76
Xitron	Vt50	44.57±5.85	0.13±2.30	31.64±3.42	0.10±1.63

Table 9. Comparison of TBW volumes calculated by different methods. From Jaffrin et al [13]

The measurement of body fluid volumes, extracellular water (ECW), intracellular one (ICW) and their sum, total body water (TBW) is important in many pathologies. TBW is strongly related to fat-free-mass (FFM) which contains, in healthy individuals, an average of 73.2% of water. The ionic composition of ICW depends upon the type of cells. Thus the ionic composition of the entire ICW is uncertain and its mean resistivity cannot be measured directly. Table 5 shows the composition of ICW in muscle cells composed of plasma and interstitial fluid and its resistivity is close to that of saline, about 40 Ω cm. Ions K^{++} replace Na^+ as the most prevalent ion as potassium is pumped into the cells. Similarly, body cell mass (BCM), which is an important nutritional parameter, is also closely connected to ICW. Independent measurements of FFM and TBW permit to detect dehydration, which is frequent in elderly persons or athletes after heavy training. Conversely, an overhydration may indicate the presence of oedema in cardiac patients. The measurement of TBW is also useful for evaluation of diuretic therapy. Renal patients treated by hemodialysis accumulate fluid between treatments. It is important to evaluate their amount of excess fluid, in order to determine how much fluid they should lose by ultrafiltration and also how this fluid loss is distributed between ECW and ICW. Measurements of BCM are also important for assessing the morbidity of patients infected by HIV.

Reference methods for measuring body fluid volumes are based on radio-isotopic dilution, deuterium (D_2O) for TBW and bromide for ECW. ICW can be measured by a radioactive potassium isotope, ^{40}K, included in body potassium or as the difference TBW-ECW. These procedures are invasive as they require blood samples and expensive, due to dosage by mass spectrometry and cannot be repeated at short intervals. Thus, they cannot be used to measure volume variations over a short period of time.

3.1.2 Bioimpedance spectroscopy (BIS) method

Since ECW and ICW fluids contains ions, they are conducting and measurements of their volume were based on their resistance or their impedance as cell membranes may act as capacitors at low and intermediate frequencies. The consequence of capacitive behaviour of membrane cells is that ECW resistance must be measured at very low frequency, <1 kHz and that of ICW and ECW combined at very high frequency (>5 MHz). However, for technical reasons, impedance meters using surface electrodes are limited to a frequency range of 5 to 1000 kHz and the ECW resistance (R_e) and the TBW one (R_∞) must be calculated by extrapolation to zero and infinite frequencies respectively.

Pichler et al [14] compared FM measurements using a SFB7 multi-frequency Impedimed impedance meter with DXA in a cohort of 32 healthy subjects and 83 patients with various diseases (kidney disease, hypertension, atherosclerosis, etc). The SB7 software overestimated FM by 6.55±3.86 kg as compared to DXA. So they developed their own BIS equation,

$$FMb= - 0.57H^2/R_C + 0.62H^2/R_0 + 0.6W - 18.43 \quad (10)$$

3.1.3 Comparison of medical impedance meters and FFI

Parker et al [15] used a 1500 Bodystat and a Tanita TBF 521 to measure FM and %BF in 42 healthy white boys 10–14 years old. The reference method was a 3C model composed of BodPod (air displacement plethysmography), TBW by D_2O, and skinfold thickness (SFT).The actual body volume (ABV) was calculated from the BodPod and a reference equation was established as

$$FM=2.22ABV-0.764TBW-1.465 \quad (11)$$

Then, they compared mean FM values and SD obtained from Eq.11 with those from BodPod, body density, TBW and skinfold, together with biases relative to reference method, and limits of agreement. All methods, except skinfold, overestimated FM. Smallest differences with the 3C, SD and limits of agreement were obtained from D_2O (0.5±1.5 kg), followed by skinfold (-0.6±3.1 kg), and the Bodystat (1.4±3.9 kg). For %BF, the Bodystat overestimated the 3C model by 2.4% and the Tanita by 4.1% The Tanita FFI overestimated FM by 2.2 kg as compared to 3C and the Bodystat by 1.4 kg. The authors concluded that both impedance meters were not accurate enough for 10-14 year-old boys, probably due to software developed for adults.

Jebb et al [16] compared the accuracy of a Tanita 305 FFI and a BIA Bodystat-1500 medical impedance meter for measuring FM on 58 overweight women during a 52 weeks period. The references were DXA and a 4C model combining measurements of body mineral content from DXA, air displacement plethysmography (ADP) skinfold thickness (SFT), and TBW by deuterium dilution. **Table 10** presents FM values measured by the 4C model, DXA, ADP, D_2O, SFT, a Bodystat and a Tanita FFI at start, after 12 weeks of weight loss and after 40 weeks of weight regain. Tanita data were closer to those of DXA and 4C than those of Bodystat as they underestimated DXA FM by only 1 kg and 4C model by 0.8 kg at start. The Bodystat underestimated DXA FM by 2.5 kg at baseline, but after 12 weeks, its FM loss was the same as DXA at 8.1 kg while Tanita FM loss was 7.3 kg. FM regain after 52 weeks was 4.8 kg for the Tanita versus 5.1 kg for the Bodystat, against 4.6 kg for DXA and 4.7 kg for 4C model. Deuterium dilution and SFT underestimated the weight loss by -1.3 kg and -2.9 kg relatively to DXA. The authors concluded that the Tanita performed better than Deuterium, SFT and the Bodystat. They attributed the superiority of the Tanita over the Bodystat to the absence of arm resistance measurement which makes a disproportionally large contribution to total resistance.

FM, kg	Baseline N=58	12 weeks N=58	52 weeks N=48	FM loss 0–12 wk	FM regain 12–52 wk
Model 4C	37.8±6.0	30.2±6.6	34.9±7.2	-7.6	4.7
BodPod	39.3±6.2	30.7±7.0	36.1±7.7	-8.6	5.4
D_2O	34.9±6.2	28.1±6.4	31.7±8.3	-6.8	3.6
DXA	38.0±5.9	29.9±6.7	34.5±7.7	-8.1	4.6
SFT	36.6±4.9	31.4±5.5	35.4±5.7	-5.2	4.0
Bodystat	35.5±5.9	27.4±6.1	32.5±6.5	-8.1	5.1
Tanita	37.0±5.9	29.7±6.4	34.5±7.0	-7.3	4.8

Table 10. Mean FM in kg at base line, after FM loss and after FM regain measured by different techniques. During the regain period, ten subjects were removed as they lost weight. Last column gives FM difference from 4C value at baseline. Adapted from Jebb et al [16]

The validity and accuracy of regional impedancemetry to measure whole body fat has been investigated by several authors. Lukaski and Siders [17] compared the FM measured by a Tanita TBF 604 FFI (Tokyo) using foot-to-foot resistances, the FM measured by a Omron HBF 301impedance meter (USA) from hand-to-hand resistances using electrodes placed on hand grips, on a cohort of 110 healthy subjects. In female subjects, the mean resistance was 516Ω for the foot-to-foot, 610 Ω for the hand-to-hand and 589 Ω for the hand-to-feet one. Corresponding mean body FM percentage (denoted %BF and calculated as FM/Wx100%) were respectively 34.9±0.9% for the Tanita, 31.2±1.0%, for Omron, versus 37.5±1.2% for DXA. Mean resistances for men were respectively 440, 460, and 475 Ω respectively. It is normal that mean resistances be higher in women than in men, who have more conducting tissues. What was unexpected is that the mean hand-to-foot resistance for men was higher than the hand-to-hand one (460 Ω), although the leg resistance is lower than the arm one. This may be due to a higher contribution of trunk resistance in men as they are taller than women. Men %BF were 24.4±1.2% with the Tanita and 20.4±1.1% with the Omron, versus 22.7±2.3% for DXA. These results confirm that FFI give %BF values closer to DXA values than the Omron.

3.2 Four electrodes FFI

Utter et al [18] compared FM measurements in 98 obese with mean BMI of 33.2± 0.6 kg m^{-2} and 27 non-obese women with mean BMI of 21.4± 0.3kg m^{-2}, using a TBF 105 Tanita FFI and underwater weighing (UW). For non-obese subjects, they reported similar results for % BF of 24.3±1.3% with the FFI and 24.0±1.5% by UW. A similar agreement between the two methods was also obtained for the obese cohort, with BF percentages respectively of 42.9±0.5% by BIA and 43.2±0.6% by UW. This result is surprising as a majority of studies reported a larger underestimation of FM by BIA, both with FFI and medical impedance meters as compared to DXA for obese subjects. The authors concluded that FFI were able to correctly measure a moderate FM decrease.

Hosking et al [19] chose a Tanita TBF-300M FFI and a Lunar Prodigy DXA to measure FFM, and %BF in two cohorts of children, 106 boys and 97 girls, of mean age 8.9±0.3 yr. All measurements were performed between 08.30 and 9.00 hr after fasting for 11 hrs with subjects in bare feet and light clothing. **Table 11** lists mean values of FFM, FM and %BF for boys and girls by DXA and BIA. FFM was overestimated by 0.6 kg in boys and by 1.3 kg in girls as compared to DXA. FM was underestimated by 0.4 kg in boys and by 0.9 kg in girls relatively to DXA. In principle, a FFM overestimation corresponds to the opposite underestimation for FM if the subject weight remains the same. Mean %BF were found to be 17.7% by Tanita and 18.6% by DXA in boys and respectively 22.4% versus 25.7% in girls. They concluded that, due to wide limits of agreement, 16.9–20.4% for boys and 20.7–24.1% for girls, the FFI was not accurate for individual children, but was acceptable for use in large scale epidemiological studies.

		Boys, n=106		Girls, n=97		
		Mean	95%Cl	Mean	95%Cl	
Weight, kg	DXA	30.7	29.4, 31.9	31.7	30.1, 33.3	
	BIA	30.9	29.6, 32.2	32.1	30.5, 33.7	
FFM, kg	DXA	24.5	23.9, 25.0	23.0	22.4, 23.6	
	BIA	25.1	24.4, 25.9	24.3	23.6, 24.9	
FM, kg	DXA	6.2	5.4, 6.0	8.7	7.6, 9.8	
	BIA	5.8	5.2, 6.4	7.8	6.7, 8.8	
%BF	DXA	18.6	16.9, 20.4	25.7	24.0,27.4	
	BIA	17.7	16.5, 18.9	22.4	20.7,24.1	

Table 11. Mean and 95% Cl for FFM, FM and %BF in boys and girls. From Hosking et al [19]

Swartz et al [20] compared FM measurements using a Tanita TBF 305, 50 kHz, 0.5 mA FFI and UW on highly, moderately, and less active subjects. The %BF was measured in athlete and adult modes of the Tanita software. The fifty seven subjects (18–35 yr old) were divided in three groups: highly active, HA >10 h of aerobic activity per week, moderately active, MA: 2.5–10h per week and less active, LA <2.5 h per week, Participants were asked not to exercise during 12 hr before the test and to abstain from alcohol 48hr before the test and to wear a swim suit for the measurement. UW uses a submersion tank containing an electronic scale placed on four transducers couple to an amplifier (Precision Biomedical systems, USA). Participants were told to expel as much air from their lungs as possible and submerge themselves and the procedure was repeated six to ten times. Detailed data are listed in **Table 12**. The athlete mode underestimated the % BF as compared to UW by 1.8 kg in highly active, 2.1 kg in moderately active, and 4.5 kg in less active subjects. The adult mode overestimated the mean %B by UV by 5.0%, in highly active group, by 4.7% in moderately active one and by 1.8 % in less active group. Tanita FFM in athlete mode overestimates UV by 1.5% in highly active, by 1.7% in moderately active and 3.7% by less active. Adult mode underestimates FFM by -4 kg in highly active, by -3.5 kg in moderately active and by only -1.6 kg in less active subjects. These data confirm that the athlete mode is adequate for exercised subjects, for both %BF and FFM and adult mode is adequate only for less exercised ones. This confirms that a FFI must use different softwares, depending on the level of exercise, to be reliable.

	N	UW	Tanita athlete	Tanita adult
Body Fat,%		Mean ±SD	Mean ±SD	Mean ±SD
Highly active	17	12.5±1.2	10.7±0.7	17.5±0.9
Moderately active	20	12.1±1.2	10.0±0.6	16.8±0.8
Less active	20	16.4±1.2	11.9±0.8	18.2±1.0
Fat-free-mass, kg Highly active	17	68.5±1.5	70.0±1.7	64.5±1.3
Moderately active	20	65.4 ±1.0	67.1±1.0	61.9±0.8
Less active	20	66.2±1.8	69.9±1.8	64.6±1.5

Table 12. % Body fat and fat-free-mass measured by UW and Tanita in athlete and adult modes. From Swartz et al [20]

Radley et al [21] tested a Tanita TBF 310 FFI against a four compartment model (4CM) combining a Lunar Prodigy DXA for measuring BMC and a BodPod for measuring in overweight and obese children, including 38 boys of 13.6±1.3 yr with a BMI of 30.3±6.0 kgm^{-2} and 14 girls of 14.7±2.2 yr with a BMI of 32.57kgm^{-2}. Mean FM measured by the 4CM equation

$$FM=2.747\ BV-0.710\ TBW + 1.46\ BMC-2.050\ W \quad (12)$$

were 31.8 ± 14.4 kg in boys and 38.3 ± 14.3 kg in girls. BV was body volume and TBW was calculated from collecting urine samples and an oral dose of deuterium. %BF was 37.5±12.0 in boys and 42.3±7.2% in girls. But the Tanita underestimated mean FM in boys by -0.8±9.3 kg and -0.5 ± 5.5 kg in girls as compared to 4CM.The Tanita underestimated %BF by -1.6± 11.0% in boys and by -0.4± 6.5 in girls. The authors concluded that SD were too large, as 40% of children had a mean %BF 4 points higher than that of 4CM, and they did not recommend this FFI for use by researchers and clinicians in overweight and obese populations. The Tanita TBF 310 was able to provide accurate estimates of mean group values, but not of individual body composition. They attributed this to the predominance of legs when measuring body resistance with a FFI.

A multicentric and multiethnic study was carried out by Boulier et al [22] on 707 subjects (255 men and 452 women) using a Tefal Bodymaster FFI (Ecully, France) and Lunar DPX and Hologic DXAs. This large cohort was composed of 400 Caucasians, 36 blacks, 101 Chinese, 72 Malaysians and 98 Indians. The comparison of FM and FFM by the FFI and DXA is shown in **Table 13**, which indicates that the Bodymaster overestimated mean FM relatively to DXA in Caucasian and black groups respectively by 0.77 and 0.98 kg, while it underestimated mean FM in Chinese, Malaysian and Indian groups respectively by -2.24, -2.54 and -3.07 kg. As expected, mean FFM was underestimated by BIA for Caucasians and blacks respectively by -0.53±3.10 and -1.08±5.30 kg and overestimated for Chinese, Malaysians and Indians, by 2.24±2.21, 2.54±2.49, 3.07±3.41 respectively, as the sum FM +FFM is equal to weight. P-values of FM and FFM were <0.001 for Eastern populations. In this case again, FM_i-FM_d differences were not equal in absolute values to FFM_i-FFM_d for Caucasians and Blacks. These differences between Caucasians and Asians are probably due to the fact that the FFI software was determined for Caucasians, and was not appropriate for Asians. The last two lines of Table 13 shows that women have much larger mean FM than men, 23.72±12.68 kg versus 14.0±8.06, but lower FFM, 42.68 ±5.41kg versus 60.05±7.86. But although they have larger FM, it is much closer to DXA than for the men, with differences 0.33 kg versus of -2.03 kg for men. This shows that it may not be necessary to determine specific FM and FFM equations for different ethnics groups, especially for Caucasian and black women, but the difference in FM and FFM with DXA is moderate and can be accepted.

Ethnic groups	FMb, BIA	FMd, DXA	FMb-FMd	FFMb, BIA	FFMd, DXA	FFMb-FFMd
Caucasians N=400	22.38±12.8	21.61±12.28	0.77±3.29	49.45±10.77	49.98±10.47	-0.53±3.10
Blacks N=36	33.85±13.4	32.87±11.75	0.98±5.30	52.73±9.88	53.82±10.16	-1.08±5.30
Chineses N=101	13.48±7.39	15.72±6.71	-2.24±2.2	46.10±9.59	43.86±9.24	2.24±2.21
Malaysians N=72s	15.59±6.91	18.13±6.53	-2.54±2.5	48.96±10.4	46.42±10.36	2.54±2.49
Indians N=98	16.71±9.22	19.77±7.11	-3.07±3.4	48.46±10.2	45.39±9.98	3.07±3.41
Women, N=452	23.7±12.68	23.38±11.55	0.33±3.39	42.68±5.41	43.00±7.01	-0.31±3.36
Men, n=255	14.00±8.06	16.03±8.21	-2.03±3.6	60.05±7.86	57.7±9.09	2.35±3.07

Table 13. FM and FFM measured in various ethnic groups and their differences. From Boulier et al [22].

3.3 Eight electrodes impedance meters

An interesting type of impedance meter consists in a FFI to which four electrodes for the hands have been added on handles attached to a vertical column. These eight-electrode devices permit to measure simultaneously foot-to-foot, hand-to-hand and two hand-to-foot resistances, from which the four limbs and trunk resistances can be determined. So it is possible to measure rapidly, in standing position, limbs and trunk FM and FFM in addition to whole body data. One of the first devices was the Tanita BC 418, with hand electrodes connected to the scale by cables, but Biospace and X-Scan (Korea) commercialize professional systems with electrodes on handles and a screen attached to a vertical column. Demura et al [23] compared a four electrode TBF101 Tanita FFI, an eight-electrode Tanita BC418 both operating at 50 kHz and a multi-frequency (MF) Biospace InBody 3.0 with DXA and HW (hydrostatic weight) in 44 healthy college students , 21 males of 65.8±9.1 kg, and 23 females of 52.6± 6.2 kg weight. They measured FFM, %BF, TBW, ICW and ECW. Data are shown in **Table 14**. The two BIA Tanita devices overestimated %BF as compared to DXA by 4.9% for the four-electrode TBF101, 2.6%for the eight-electrode BC418, and 1.38% for the InBody in men. In women, the TBF101 overestimated %BF by 2.2%, the BC418 by 2.82% and the InBody underestimated %BF by -1.04%, which confirms the advantage of eight- electrodes devices over a four-electrodes FFI. However, the authors could not explain why %BF was overestimated in women as compared to DXA with both 50kHz devices while it was underestimated by the MF InBody. They suggested that it could be due to the larger %BF in women. HW overestimated DXA by 0.89% in men and underestimated it by -2.32 % in women. Authors concluded that the MF InBody was superior to the other impedance meters tested.

%BF	SF-BIA4 Mean ±SD	SF-BIA8 Mean ±SD	MF-BIA8 Mean ±SD	DXA Mean ±SD	HW Mean ±SD
Total, n=44	19.49 ±4.47	18.75±6.05	16.16±4.87	16.04±6.16	15.25±5.27
Male, n=21	15.97±2.63	13.67±2.47	12.45±2.50	11.07±2.43	11.96±3.91
Female, n=23	22.71±3.17	23.39±4.33	19.53±3.96	20.57±4.87	18.25±4.54
Test-retest reliability	0.995	0.994	0.995	0.996	0.996

Table 14. Mean values and SD of mean %BF using a SF four electrode BIA, a SF eight electrode BIA, a MFeight electrodes BIA and DXA. From Demura et al [23]

Völgyi et al [24] measured FFM and %BF from TBW measurements using an eight-electrode Tanita BC418 and an InBody 720 multi-frequency impedance meter in 82 men and 80 women of 37-81 yr age span and compared them with those of a Lunar Prodigy DXA. Each cohort was divided in three categories, normal, overweight and obese, according to their mean %BF measured by DXA. Detailed data are given in **Table 15**. FFM of InBody and Tanita were systematically overestimated as compared to DXA for both men and women. Mean %BF values were respectively 22.2%, 27.4% and 33.3% in men and 32%, 40.3% and 44.9% in women. When compared with DXA data, the Tanita underestimated mean %BF in men by 4.1% in normal and overweight subjects, and 2.1% in obese ones. InBody underestimations were 4.3% for normal and overweight and 1.6% in obese subjects. In women, %FM underestimations by the Tanita were respectively 3.7, 4.6 and 3.3%. Underestimations by the InBody were respectively 5.9, 5.0 and 3.1%, larger than with the Tanita. It is interesting to note that both impedance meters gave smaller %BF underestimation with obese subjects than with overweight and normal ones, which disagrees with other articles. They also concluded that %BF differences of their devices with DXA were smaller than in other articles.

	Men, n=82			Women, n=86		
	Normal, N=31	Overweight N=40	Obese N=11	Normal, N=44	Overweight N=27	Obese N=15
FFM, kg						
DXA	58.5±4.9	61.9±8.3	63.5±3.6	41.1±4.5	41.9±3.5	46.5±5.1
InBody	61.7±5.6	64.8±8.7	63.5±3.6	44.5±5.0	45.2±4.2	50.0±7.0
Tanita	60.5±5.0	64.5±7.2	65.4±3.8	28.3±5.1	44.8±3.2	49.9±6.0
%BF						
DXA	22.2±4.8	27.4±4.9	33.3±5.3	32.0±6.1	40.3±3.0	44.9±5.8
InBody	16.4±5.1	23.1±5.2	31.7±6.1	26.1±5.6	35.3±3.5	41.8±5.0
Tanita	18.0±4.5	23.3±4.2	31.2±5.1	28.3±5.1	35.7±2.8	41.6±3.9

Table 15. Comparison of FFM and %BF measured by DXA, a 720 InBody and a BC 418 Tanita eight electrodes impedance meters in normal, overweight and obese subjects. From Volgyi [24]

Lim et al [25] used a multi frequency (1, 5, 50, 250, 500 and 1000 kHz) InBody 720 with eight tactile electrodes in 166 healthy Korean children (86 male and 80 female) aged 6-18 yr to measure FFM and FM and compared their data with those of a GE Lunar Prodigy DXA. Subjects with chronic disease that would affect body composition were excluded. Children were divided in ten groups according to age and sex. The InBody displayed automatically FFM, FM and %BF. FFM was estimated from TBW using a prediction equation developed for Asian subjects. The DXA measured BMC, FM and lean mass. Results of this comparison are given in **Table 16**. The InBody overestimated FM in each group as compared to DXA. It is interesting to note that mean FM_i and FM_d were maximal in boys of 13±1 year age. In boys, the InBody overestimated FM_i, as compared to DXA by respectively 1.1, 0.6, 0.1, 1.5, and 0.6 kg in the five groups with a mean of 0.9 kg. This FM overestimation is unusual as many authors have reported FM underestimation by BIA in normal subjects. The 4th group had a low mean DXA FM of 7.3 kg and consequently the highest FM overestimation (1.5 kg) by the InBody. The same phenomenon was not observed with girls who presented a regular increase in FM with age. As expected, their 5thgroup had the highest FM_d of 13.9 kg by DXA and the largest FM_i overestimation by the InBody of 1.6 kg relative to DXA with a general mean of 0.8 kg for 80 girls. It is interesting to note that, for both boys and girls the 3rd group had the smallest FM_i overestimation at 0.1 kg. Authors regretted not to have compared lean and obese subjects at the same age. Authors concluded that, although BIA and DXA were not interchangeable for %BF or FM, these techniques provided similar estimations of FFM, FM and %BF in healthy children and that BIA could be used in screening and DXA for definite diagnosis and need of intervention.

groups	1st	2nd	3rd	4th	5th	Total
Boys Mean age, yr	n=37 8.7±1.5	N=10 11.1±1.5	N=10 12.9±1.1	N=11 14.9±1.2	N=18 15.5±1.1	N=82 11.7±3.2
DXA FM_d, kg	5.5±4.1	7.1±4.2	12.0±5.8	7.3±3.9	11.1±7.8	7.8±5.7
BIA FM_i ,kg	6.6±4.2	7.7±4.9	12.1±6.0	8.8±3.0	11.7±7.3	8.7±5.6
FM_i-FM_d, kg	1.1	0.6	0.1	1.5	0.6	0.9
Girls, mean age,yr	N=25 8.2±1.2	N=17 9.7±1.2	N=8 11.0±1.2	N=12 12.8 ±1.8	N=18 15.2±1.5	N=80 11.1±3.0
DXA FM_d,kg	3.4±1.4	5.8±2.5	8.7±5.2	11.0±6.2	13.9±3.2	8.0±5.4
BIA FM_i ,kg	3.9±1.5	6.7±2.8	8.8±3.2	11.7±6.2	15.5±3.0	8.8±5.5
FM_i-FM_d, kg	0.5	0.9	0.1	0.7	1.6	0.8

Table 16. Comparison of DXA and BIA FM in kg and % of body weight in five age groups. Adapted from Lim et al [25].

Shafer et al [26] also used a MF InBody 320 and a DXA (QDR Delphi, USA) in a group of 132 healthy adults divided first by sex and then in three groups, normal (BMI =18.7–24.9kgm^{-2}), overweight (BMI=25.1–29.8), and obese (BMI= 30.1–39.3 kgm^{-2}). **Table 17** shows that mean %BF was overestimated relatively to DXA by 0.87% in women, and by 0.75% in men. Men FM_i was overestimated by 1.46±0.27 kg in women and 1.44±0.27 kg in men relatively to DXA. FM_i in normal subjects was underestimated by -0.69±0.32 kg, but was overestimated by 0.95±0.33 kg in overweight subjects and by 4.11±0.34 kg in obese ones relatively to DXA. They concluded that InBody FM_i was valid for normal and overweight groups, but not for obese subjects, as their smaller trunk resistance may have increased the FM value.

Variable	Women, n=69	Men, n=61	Normal BMI n=46	Overweight BMI,n=44	Obese, BMI, n=42
DXA % BF	35.60±0.58	22.62±0.60	22.39±0.71	29.63±0.72	35.32±0.73
InBody % BF	36.46±0.60	23.37±0.63	20.83±0.74	30.21±0.76	38.72±0.77
% BF_i-%BF_d	0.87±0.31	0.75±0.32	-1.56±0.32	0.58±0.39	3.40±0.39
DXA FM_d, kg	26.19±0.55	20.77±0.57	14.75±0.67	22.54±0.69	33.16±0.69
InBody FM_i, kg	27.66±0.60	22.21±0.62	14.06±0.73	23.49±0.75	37.27±0.76
FM_i– FM_d	1.46±0.27	1.44±0.27	-0.69±0.32	0.95±0.33	4.11±0.34

Table 17. Comparison of %BF and FM in kg obtained from DXA and InBody for women and men according to three ranges of BMI. From Schafer et al [26]

Neovius et al [27] measured %BF of 106 abdominally obese women of initial mean BMI of 30.4±2.9 kgm^{-2} with age ranging from 27 to 60 yr, using a BC418 eight electrodes Tanita. Participants were asked to dress in underwear without metal in their clothes and to walk 5000 steps per day. These measurements, taken initially and after a 6 months follow-up period, were compared with those of a Lunar GE Prodigy DXA and are displayed in **Table 18**. The aim was to assess the agreement between DXA and the Tanita for Δ%BF over six months. The Tanita underestimated systematically the mean %BF, relatively to the DXA, by -5.0% initially and by -4.39% after follow-up. The difference between DXA and the Tanita increased with adiposity. Authors concluded that differences in %BF between Tanita and DXA were significant as the highest p-value was 0.015 and that new prediction equations should be developed for obese subjects.

	Initial values		Follow-Up		Difference
	Mean±SD	Range	Mean±SD	Range	Mean±SD
Age, yr	48.2±7.6	27 to 60			
Height, m	1.67±0.07	1.51 to 1.85			
Body weight,kg	84.6±10.0	65.0 to 108.0	83.9±10.7	57.9 to 105.6	-0.7±3.4
BMI kgm^{-2}	30.4±2.9	24.8 to 36.7	30.1±3.3	22.2 to 37.2	-0.3±1.2
%BF, BIA	40.8±3.4	32.8 to 48.3	40.3±4.6	25.8 to 50.0	-0.5±2.2
%BF,DXA	45.8±3.6	36.1 to 54.7	44.7±4.8	30.1 to 54.7	-1.1±2.5
$\%BF_i - \%BF_d$	-5.0		-4.39		

Table 18. Comparison of %BF obtained from DXA and the Tanita initially and after a 6 months follow-up. Last column= difference between follow up and initial values. FromNeovius et al [27].

Bousbiat et al [28] compared the FFM calculated from the hand-to-foot resistance R_{13} and from the foot-to-foot one R_{34} with DXA FFM_d. They used a Tefal prototype consisting in the electronics and foot plate of a Tefal BodyVision FFI with eight electrodes. The first goal was to see if R_{34} provided a less accurate as compared to DXA than R_{13} used by medical devices. Since FFI do not take into account the arm and upper trunk resistance, it is legitimate to assume that the hand-to-foot resistance better reflects the whole body composition than the foot-to-foot one. However, several authors [26, 28] have pointed out that the trunk longitudinal resistance accounts for only 4 to 6% of hand-to-foot resistance, while the trunk represents about half of body FFM. Thus a relatively large variation in trunk resistance due to a different morphology will only slightly modify R_{13}. In addition, the arm resistance is 5 to 10% higher than the leg one, but its FFM is, on average, about 2.7% smaller [27].

The modified BodyVision FFI with hand electrodes described earlier was used to compare the accuracy of both methods. Corresponding equations using R_{13} determined for the first group are shown below for women.

Corresponding equations for R_{13}, determined on the BF 85 cohort are as follows

K_1 $\quad FFM_i = 0.6679[(H^2\sqrt{W})/ R_{13}]^{2/3} -0.0346Age +12.42$ (13a)

K_2 $\quad FFM_i =0.7978[(H^2\sqrt{W})/ R_{13}]^{2/3} -0.0255Age +0.0139 R_{13} -3.46$ (14a)

K_3 $\quad FFM_i =0.8141[(H^2\sqrt{W})/ R_{13}]^{2/3} -0.0246Age +0.0144 R_{13}-0.0078W-4.09$ (15a)

L_1 $\quad FFM_i= 0.4678 (H^2/ R_{13}) + 0.1905W - 0.0384Age + 12.87$ (16a)

L_2 $\quad FFM_i= 0.6527 (H^2/ R_{13}) + 0.1857W - 0.0242Age + 0.0153R_{13} - 5.21$ (17a)

And for R_{34}

K_1 $\quad FFM_i =0.4804 [(H^2\sqrt{W})/ R_{34}]^{2/3} -0.0558Age +18.38$ (13b)

K_2 $\quad FFM_i =0.6506[(H^2\sqrt{W})/ R_{34}]^{2/3} -0.0361Age +0.0258 R_{34} -7.67$ (14b)

L_1 $\quad FFM_i = 0.2213 (H^2/ R_{34}) + 0.2355W - 0.0574Age + 18.45$ (15b)

Another goal was to compare the prediction accuracy of six regression equations for FFM. A 1st cohort of 85 men (BM85) and 85 women (BF85) was used for calculating coefficients in Eqs 13–17 by comparison with DXA data while a 2nd cohort of 42 men (VM42) and 44 women (VF44), of same mean age as the 1st cohort, was used for an independent validation of the method.

Corresponding equations for K_3 and L_2 methods are not given here for proprietary reasons, but FFM_i values obtained from them will be shown in **Tables** 19 and 20.

	N=44	K_1	K_2	K_3	L_1	L_2	Mean values	Tefal
R_{13}	FFM_i, kg	43.04± 4.39	42.85± 4.82	42.85± 4.83	43.07± 4.87	42.86± 4.89		
	FFM_i-FFM_d, kg	0.67 ±2,58	0.48 ±2,24	0.49 ±2,25	0.71 ±2,42	0.49 ±2,28	0.517	
	P	0.091	0.159	0.159	0.059	0.158	0.125	
R_{34}	FFM_i, kg	42.20± 4.05	42.15± 3.96	42.41± 4.07	42.58± 4.15	42.42± 4.08		42.09± 4.74
	FFM_i-FFM_d, kg	-0.17 ±2.31	-0.22 ±2.04	-0.05 ±1.95	0.22 ±1.99	0.05 ±1.94	0.126	-0.27 ±1.83
	P	0.631	0.488	0.870	0.475	0.859	0.665	0.329

Table 19. Meandifferences and SD between FFM by impedance and by DXA and Tefal Body Vision for women of 2nd cohort (VF44). From Bousbiat et al [28]

	N=42	K_1	K_2	K_3	L_1	L_2	Mean values	Tefal
R_{13}	FFM_i, kg	60.57±7.64	60.33±7.8	60.74±7.9	60.84±7.93	60.73±7.88		
	FFM_i-FFM_d, kg	0.02 ±3.00	-0.22 ±2.66	0.19 ±2.52	0.29 ± 2.71	0.18 ±2.50	0.180	
	P	0.964	0.590	0.626	0.486	0.641	0.661	
R_{34}	FFM_i, kg	60.84± 6.690	60.46± 7.17	60.58± 7.28	60.95± 7.07	60.61 ±7.27		60.20 ±7.72
	FFM_i-FFM_d, kg	0.29 ±3.52	-0.09 ±2.93	0.03 ±2.74	0.19 ±3.22	0.06 ±2.77	0.132	-0.35 ±2.41
	P	0.589	0.842	0.942	0.380	0.884	0.727	0.341

Table 20. Mean differences and SD between FFM by impedance and by DXA and Tefal BodyVision for men of 2nd cohort (VM42). From From Bousbiat et al [28]

It is seen that the mean differences FFM_i-FFM_d and their SD are smaller when obtained from R_{34} than when using R_{13} for both female and male subjects. This is confirmed by p-values which are larger for R_{34} at 0.859 (Female) and 0.884 (Male) when using L2 equations. However, p-values with R_{13} were 0.158 and 0.641, indicating that differences relative to DXA data were not significant. It is interesting to note that L1 equations without the linear resistance term have lower p-values and larger mean bias than L2 equations. Correlations of FFM_i versus FFMd are shown in **Figs 9 and 10** for female and male, respectively. Bland-Altman graphs of of differences calculated with K3 equations and DXA for the validation cohorts using R_{13}, and R_{34} resistances are shown in **Fig. 11** for female cohort and **Fig. 12** for male one. For both female and male subjects, there is only one point (2.3% of data) lying outside the limits of agreement (mean±2SD). This confirms a normal distribution as the percentage of points outside these limits is less than 5%.

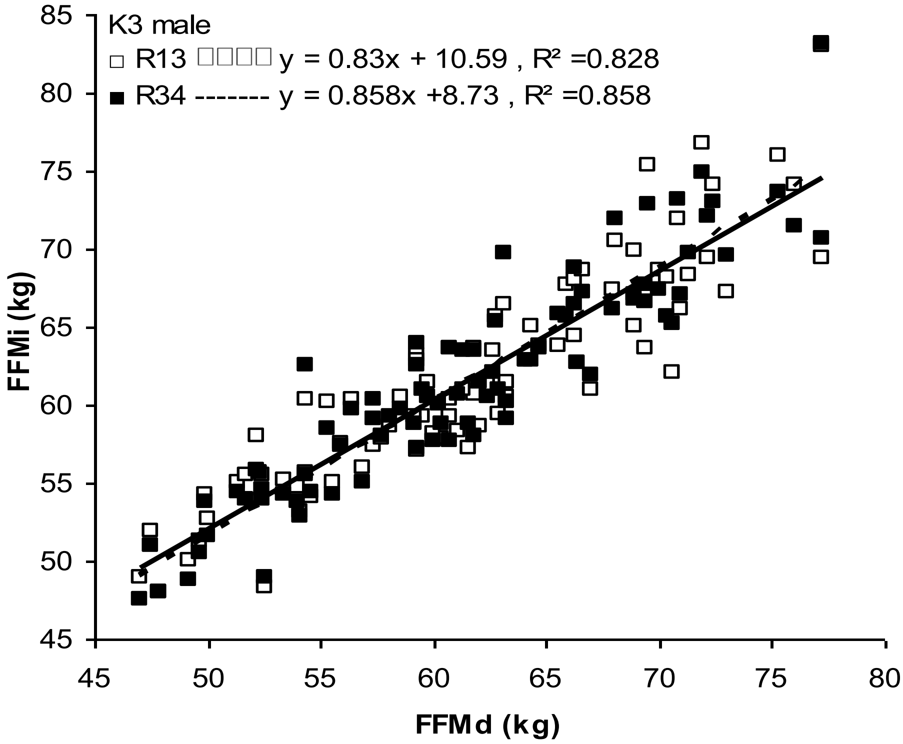

Fig. 9. Correlation of FFM_i with FFM_d for female F 85 cohort using K_3 equation with R_{13} and R_{34}. From Bousbiat et al [28]

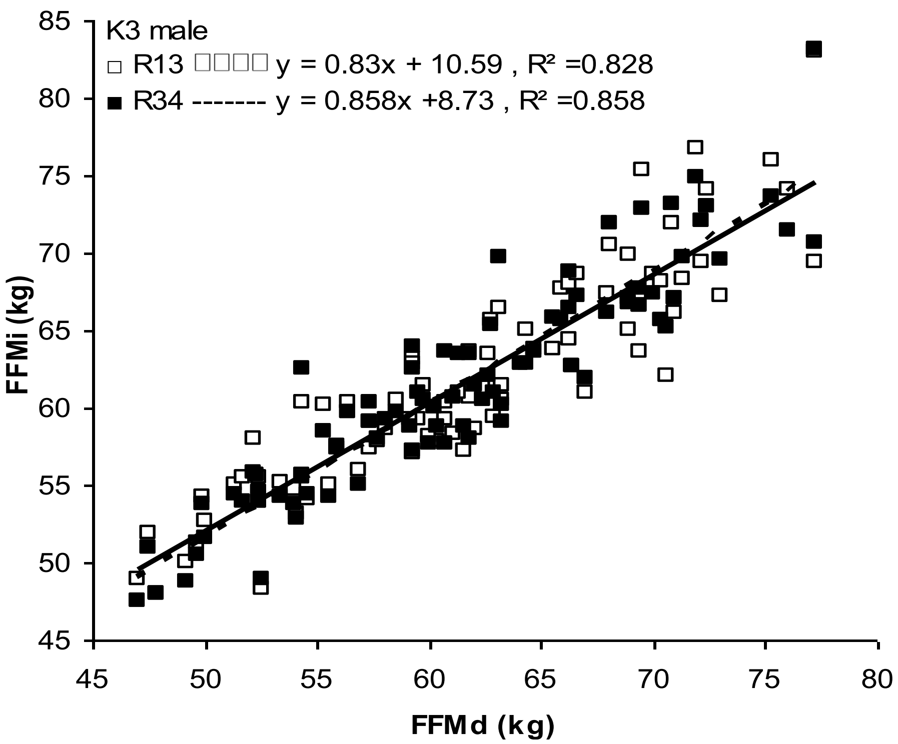

Fig. 10. Correlation of FFM_i with FFM_d for male M 85 cohort using K_3 equation with R_{13} and R_{34}. From Bousbiat et al [28]

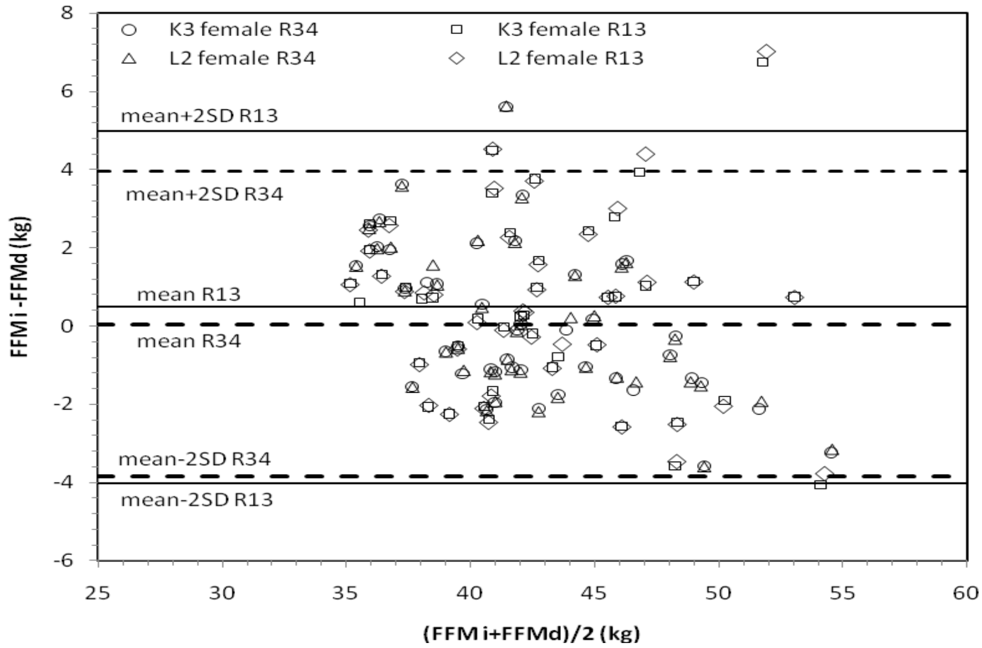

Fig. 11. Bland-Altman graphs of differences between FFM calculated by K_3 and L_2 equations and DXA in a cohort of 44 females using R_{13} and R_{34} From Bousbiat et al [28]

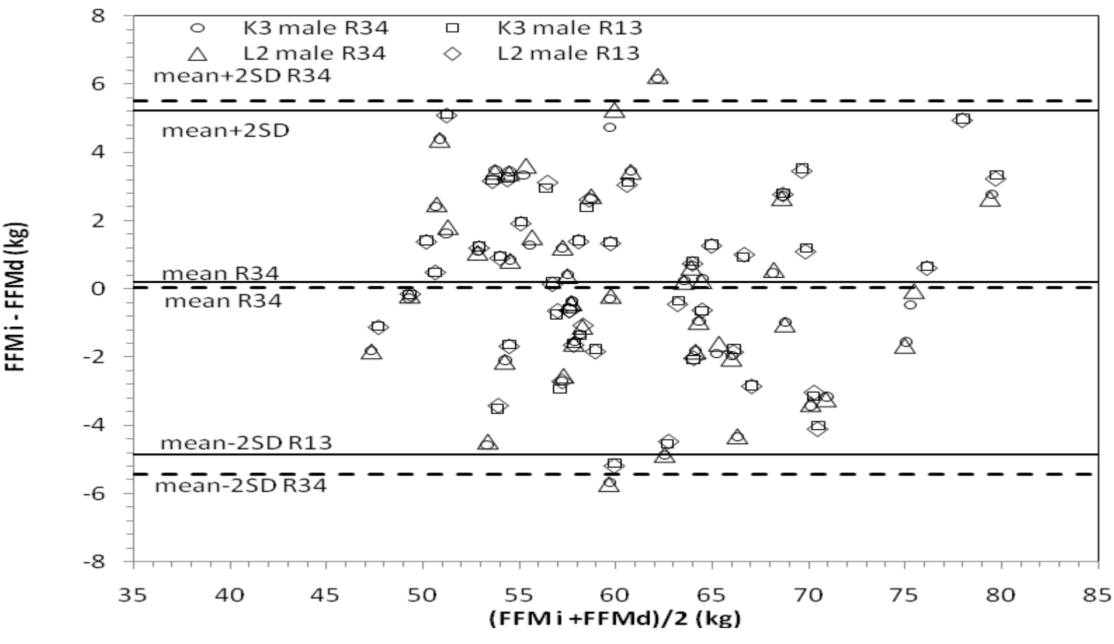

Fig. 12 Bland-Altman graphs of differences between FFM calculated by K_3 and L_2 equation sand DXA in a cohort of 42 males using R_{13} and R_{34}. From Bousbiat et al [28]

Mean values of FFM_i obtained from R_{13} by all equations, were slightly higher than those of DXA. With R_{34}, K type equations produced a small underestimation of FFM_i, against a slight overestimation for L type equations. For women, mean differences and SD with FFM_d are lower when R_{34} is used than when it is R_{13} and they are smallest for K_3 and largest for the Tefal BodyVision in last column. For men, equations K_3 and L_2 also gave closest FFM with DXA for R_{34}. Lukaski et al [29] validated body composition by impedance in dialysis.

3.4 FM and FFM measurements in limbs and trunk with eight electrodes FFI

Sato et al [30] measured limbs and trunk FFM and FM with an eight electrodes BC 118 Tanita in 43 male and 29 female obese Japanese adults and comparing their data with a Lunar Radiation DXA. The Tanita underestimated the male mean body FM at 22.4±3.3 kg versus 24.8±3.9 kg by DXA, while it slightly overestimated it in females at 27.6± 5.1 kg versus 27.2±4.9 kg for DXA. The Tanita gave a mean leg FM of 3.7±3.65 kg for males and 4.7±0.8 kg for females against 3.4±0.7 kg and 4.25±1.1 kg by DXA. Corresponding data for arms FM in males were 0.9±0.2 kg (left arm) and 0.95±0.2 kg (right) and, in females, 1.2±0.3 kg (left) and 1.35±0.3 kg (right). Trunk+ head FM was calculated by subtracting the sum of limbs FM from total body FM. The Tanita underestimated this FM in males at 13.3±2.1 kg versus 15.7±2.4 kg by DXA, and overestimated it in females at 15.7±3.0 kg versus 15.1±2.5 kg by DXA. Authors concluded that the accuracy of trunk FM was inferior to that of limbs and total body FM.

Pietrobelli et al [31] also used an eight electrodes 50 kHz BC 418 Tanita to measure FFM and %BF in limbs and trunk + head in a normal population of 20 males and 20 females. These results are displayed in **Table 21** which shows that FFM in limbs and trunk+ head were close to those measured by DXA. The BC 418 underestimated the mean FFM in arms by 0.2 kg as compared to DXA, but overestimated it in legs by 0.3 kg and by 2.2 kg in trunk+head. T-Student tests showed that differences were not significant as p-values were above 0.6. They also plotted skeletal muscle mass (SM) by Tanita versus that by DXA. The relation was $SM_{BIA} = 0.95SM_{DXA}+1.5$ with p=0.9. %FM of limbs, trunk+ head and total body are shown in 5th and 6th columns of Table 21. As expected, the BC 418 overestimated fat percentage in arms since their FFM was underestimated, while fat percentages in legs were close to those by DXA. The BC 418 underestimated %BF of trunk+ head at 25.2±9.7% against 28.9± 10.8 for DXA, but differences were not significant as p= 0.13. P-values were maximum at 0.97 for legs and 0.63 for total body. It would have been interesting to compare body %BF by the BC 418 and DXA, but these data were not supplied. The authors concluded that segmental eight electrodes systems provide important new research and clinical opportunities.

Segment	FFM,kg DXA	FFM, kg BC 418	P /DXA vs BC 418	%BF DXA	%BF BC 418	P/DXAvs BC 418
Left arm	2.6±1.4	2.4±1.2	0.60	26.6 ±12.1	30.4±10.3	0.29
Right arm	2.6±1.3	2.4±1.2	0.61	26.3±11.9	29.2±10.0	0.41
Left leg	7.4±2.9	7.7±2.9	0.75	30.8±10.8	30.9±10.0	0.97
Right leg	7.4±2.8	7.8±2.8	0.65	30.6±10.9	30.5±10.2	0.97
Trunk +head	24.5±9.3	2 6.7±8.5	0.60	28.9±10.8	25.2±9.7	0.13
Total body Skeletal mass	23.8±9.7	25.2±9.6	0.90			

Table 21. Mean FFM of limbs and trunk+head and mean %BF measured by DXA and the Tanita BC418. P-values of T-test comparing FFM and %BF by DXA and Tanita. Adapted from Pietrobelli et al [31].

Ling et al [32] used a 720 InBody and a Hologic QDR 4500 DXA to measure whole body FFM, FM and %BF in 242 female and 242 male normal adults aged 62± 6.5 yr, together with limbs and trunk FFM. Results are listed in **Table 22** which shows that the InBody overestimated mean FM as compared to DXA by 1.2 kg in women and by 2.4 kg in men. But curiously, mean FFM was underestimated in women by -0.7 kg instead of -1.2 kg. In men, mean FFM was underestimated by -1.4 kg instead of -2.4 k. %BF were overestimated with the InBody by 1.2% in women and by 2.6% in men. Arms FFM measured by the InBody were close to those of DXA with a 0.1kg mean overestimation in women left arm and a 0.2 kg underestimation in men right arm. The InBody underestimated mean legs FFM by 0.5 kg in women and 0.55 kg in men, while mean trunk FFM (without the head) was underestimated by 2.8 kg in women and 3.7 kg in men. The overestimation by BIA rose when BMI increased. This overestimation could be partially corrected by introducing BMI in FFM and FM software of the InBody. The authors also separated their subjects not by sex, but according to BMI in **Table 23**. This table shows that BIA FFM, FM and %BF were respectively 0.2 kg, 0.45kg and 0.4% above DXA values in the normal group. However it is strange again that both FFM and FM were overestimated as the sum is equal to weight. In the overweight group, BIA underestimated FFM by -1.24 kg and overestimated FM by 1.98 kg and %BF by 2.15%, as compared to DXA, which is logical. The same trend was observed in the obese group but to a larger extent, with a FFM underestimation of -4.07 kg, a 5 kg overestimation for FM and 4.85% for %BF. The authors concluded that direct segmental multi-frequency BIA was a valid tool for measuring whole body and limb and trunk composition and showed good correlation with other reference methods such as total body potassium and isotope dilution techniques.

Parameter Body segment	Female, N=242		Male, N=242	
	DXA	BIA	DXA	BIA
Weight, kg	72.2±12.5	72.7±12.6	84.5±10.8	85.5±10.9
Body FFM, kg	47.2±5.8	46.5±5.2	65.0±6.8	63.6±7.0
Body FM, kg	25.0±7.8	26.3±9.5	19.5±5.9	21.9±7.3
%BF	33.9±5.5	35.1 ±7.3	22.7±4.6	25.3±6.2
Right arm, FFM, kg	2.5±0.4	2.5±0.4	4.0±0.6	3.8±0.5
Left arm, FFM, kg	2.3±0.4	2.4±0.4	3.8±0.5	3.7±0.5
Right leg, FFM, kg	7.6±1.1	7.0±0.9	10.4±1.3	9.8±1.2
Left leg, FFM, kg	7.4±1.1	7.0±0.9	10.2±1.3	9.7±1.2
Trunk, FFM, kg	24.1±3.0	21.3±2.5	32.5±3.5	28.8±3.1

Table 22. Mean values and SD of weight, Body FFM and FM, %BF and limbs and trunk FFM. From Ling et al [32]

Subjects	Normal, n=168 BMI:18.5-24.9		Overweight, n=246 BMI:25-29.9		Obese, n=67 BMI: >30.	
	DXA	BIA	DXA	BIA	DXA	BIA
FFM, kg	51.2±9.57	51.45±9.64	58.21±10.30	56.97±10.20	61.55±10.94	57.48±11.24
FM, kg	17.0±4.14	17.49±4.34	22.69±4.74	24.67±4.71	34.16±7.58	39.16±8.55
%BF	25.3±6.61	25.70±6.73	28.43±6.88	30.28±6.67	35.81±7.04	40.66±7.65
ICC	FFM:0.99, FM:0.95 %BF: 0.96		FFM:0.99, FM:0.90 %BF: 0.94		FFM:0.96, FM:0.89 %BF: 0.87	

Table 23. FFM, FM and %BF measured by DEXA, and BIA in men and women together according to BMI. From Ling et al [32]

Gibson et al [33] compared %BF measurements from a 320 and a 720 InBody with those from a 4C model combining BMC from DXA, UW and TBW from BIS. Adult subjects consisted of 25 whites, 24 blacks, and 24 Hispanics for each sex. **Table 24** provides %BF values for men and women calculated from Selinger 4C model and measured using the InBody 720 and 320. Mean men %BF was slightly underestimated by the InBody 720 as compared to the 4C model in white by -2.13%and in black by -0.34% but was slightly overestimated for Hispanics by 1.4%. With the InBody 320, corresponding differences were -2.26% for whites, 0.01% for blacks and 1.32% for Hispanics. Mean women %BF was underestimated for all subjects as compared to the 4C model by -1.63 % in whites, -4.63% in blacks and -2.45% in Hispanics with the InBody720. With the InBody 320, corresponding underestimations were -2.58% in whites, -2.86% in blacks and 2.03% in Hispanics. The mean total %BF for men was slightly underestimated at 21.0% by both InBodys against 21.34% for the 4C. In women, the total %BF was underestimated at 32% by the 720 and at 32.5% by the 320 against 35.04% for the 4C. Authors concluded that, although both InBodys underestimated %BF of 4C, and black women presented a challenge for the 720 and the 320, the rapidity of their measurements was worthwhile. They also concluded that to increase the accuracy of BIA measurements, the participants should receive and follow the standard guidelines.

	Men n=73			Women n=73		
Method	4C Selenger, %BF	InBody 720, %BF	InBody 320 , %BF	4C %BF	InBody 720, %BF	InBody 320, %BF
White	23.84±8.28	21.71±8.39	21.58±8.18	33.99±8.82	31.76±9.74	31.41±9.66
Black	18.12±8.82	17.78±7.54	18.13±7.14	34.79±8.58	31.76±9.74	31.93.±10.0
Hispanic	22.01±10.02	36.39±9.81	34.36±9.11	36.39±9.81	33.94±9.31	34.36±9.11
Total	21.34±9.25	20.98±8.85	21.02±8.56	35.04±9.01	32.05±9.82	32.55±9.55

Table 24. Percentage BF by method and sex for white, black and Hispanic adults. From Gibson et al [33]

Organ et al [34] have shown that virtual limb resistances can be measured with only peripheral electrodes at ankles and wrists, which is faster and does not need undressing, as it avoids the need of shoulder and waist electrodes. It assumes that, if current electrodes are ipsilateral and located on right hand and foot, no current will circulate between right shoulder and left hand which will have the same potential. So the right arm resistance will be measured with contra-lateral voltage electrodes on right and left hands. Similarly, the right leg resistance will be measured with same current and voltage electrodes on right and left feet.

A possible explanation for a better accuracy of FFI is that they avoid the higher variability of arm resistances measurements. Jaffrin and Morel [35] reported that standard deviations of arm resistances in a normal adult population, measured with an eight-electrode BodyVision FFI, were 16.2% in left arm and 18.6% in right arm, against 9.4% in left leg and 7% in right leg.

They used an 8-electrodes Tefal prototype based on a Bodymaster Vision to measure body composition in limbs and trunk in a cohort of 257 healthy adults aged from 19 to 75 years.

By measuring sequentially the resistances of five current paths between pairs of voltage electrodes 1-2, 1-3, 1.4, 2-4, 3-4, one obtains a set of five equations for the four limbs and trunk resistances, right arm R_{ra}, left arm R_{la}, trunk R_t, right leg R_{rl}, left leg R_{ll}

$$R_{ra} + R_{la} = R_{12} \tag{18}$$

$$R_{ra} + R_t + R_{rl} = R_{13} \tag{19}$$

$$R_{ra} + R_t + R_{ll} = R_{14} \tag{20}$$

$$R_{rl} + R_{ll} = R_{34} \tag{21}$$

$$R_{la} + R_t + R_{ll} = R_{24} \tag{22}$$

R_{23} was not used as current passes near the heart which may modify it. The resolution of this system gives values of arms, legs and trunk resistances as function of current paths resistances as

$$R_{ra} = (R_{12} + R_{14} - R_{24})/2 \tag{23}$$

$$R_{la} = (R_{12} - R_{14} + R_{24})/2 \tag{24}$$

$$R_{rl} = (R_{34} + R_{13} - R_{14})/2 \tag{25}$$

$$R_{ll} = (R_{34} - R_{13} + R_{14})/2 \tag{26}$$

$$R_{t} = (R_{13} - R_{12} - R_{34} + R_{24})/2 \tag{27}$$

FM_i were calculated from equations derived by comparison with DXA data, using the same cohorts as for FFM_i. These equations are listed below for men, successively for arms and legs, where FM_B is the body FM measured by a Tefal Bodymaster Vision FFI

$$FM_{ra} = 0.0547FM_B - 0.0232BMI + 0.00246\ Age + 0.30,\ R^2=0.78 \tag{28}$$

$$FM_{la} = 0.0627FM_B - 0.0416BMI + 0.00209\ Age + 0.579,\ R^2=0.76 \tag{29}$$

$$FM_{rl} = 0.0201FM_B - 0.1289BMI - 0.01346Age + 2.71,\ R^2=0.70 \tag{30}$$

$$FM_{ll} = 0.186FM_B - 0.1135\ BMI - 0.0142\ Age + 2.50,\ R^2=0.71 \tag{31}$$

For women, they are

$$FM_{ra} = 0.0354FM_B + 0.098BMI + 0.0014\ Age - 0.63,\ R^2=0.85 \tag{32}$$

$$FM_{la} = 0.0436FM_B + 0.0255BMI + 0.0010\ Age - 0.475,\ R^2=0.82 \tag{33}$$

$$FM_{rl} = 0.0809FM_B + 0.140BMI - 0.0132\ Age - 0.459,\ R^2=0.71 \tag{34}$$

$$FM_{ll} = 0.0982FM_B + 0.081\ BMI - 0.012\ Age + 0.339,\ R^2=0.71 \tag{35}$$

Limbs FFM and FM were calculated from resistance and DXA measurements by dividing the 257 subjects in two cohorts of 85 men and 85 women for determining the equations and two others of 43 men and 44 women for validation of accuracy of FFM_i and FM_I by impedance as compared to DXA by using T-Student test. Limbs impedance FFM_j where j denotes successively ra, la, rl and ll were given by a BIS type equation

$$FFM_j = k_j\ (H^2W^{1/2}/R_j)^{2/3} \tag{36}$$

Mean values and SD of limbs FFM_i of 1st cohort of 85 men and 85 women as well as of their differences with DXA and p values of Student t-tests for comparison with DXA FFM_d are given in **Table 25**. Similar data are given for 2nd cohort of 43 men and 44 women at the bottom of Table 25. Schematic of limb resistances are shown in **Fig. 13** and electrode positions for medical impedance meters can be seen in **Fig. 14**. There are no significant differences between BIA and DXA, as p-values ranged from 0.412 to 0.690 in 1st cohort and from 0.762 to 0.815 for 2nd cohort in men. P-values were lower for women. **Table 26** gave similar information for limbs FM and p-values were very high for the 1st cohort in both men and women which means that BIA FM were very close to those of DXA. **Table 27** gave similar data for trunk FFM and FM for the 1st and 2nd cohorts, and p-values were high, especially for FM. Trunk FFM_{ti} were calculated from combined trunk and limb FFM_{tl} using resistance R_{24} from left hand to left foot. Then FFM_{ti} was determined by subtracting the sum of limbs FFM from FFM_{tl}. Mean FFM_{ti} differences with DXA were 0.127 kg for men and 0.110 kg for women of 1st cohort against -0.226 kg for men and 0.392 kg for women of 2nd cohort, p-values of mean FFM_{ti} ranged from 0.743 to 0.731 for the 1st cohort, but were smaller for the 2nd cohort as expected.

		Right arm	Left arm	Right leg	Left leg
1st cohort Men n=85	FFM, kg FFMi-FFMd p/DXA, R^2	3.8 ±0.59 0.031±0.497 0.572, 0.28	3.66±0.64 0.043±0.482 0.412, 0.43	10.23±1.44 0.032±0.814 0.715, 0.65	10.08±1.43 0.036±0.836 0.690, 0.66
1st cohort Women n=85	FFM, kg FFMi-FFMd p/DXA, R^2	2.18±0.376 0.018±0.273 0.533, 0.47	2.05±0.359 0.019±0.307 0.571, 0.27	6.97±1.24 0.054±0.728 0.495, 0.65	6.76±1.15 0.039 ±0.625 0.570, 0.70
2nd cohort Men n=43	FFM, kg FFMi-FFMd p/DXA R^2	3.74±0.77 -0.018±0.485 0.811 0.61	3.58±0.58 -0.020±0.560 0.815 0.08	10.13±1.40 -0.039±0.846 0.762 0.64	9.97±1.22 -0.037±0.820 0.767 0.55
2nd cohort Women n=44	FFM, kg FFMi-FFMd p/DXA R^2	2.22±0.374 0.068±0.280 0.116 0.42	2.049±0.328 0.013±0.261 0.745 0.36	6.89±1.04 0.089±0.547 0.285 0.72	6.618±0.977 -0.152±0.559 0.078 0.68

Table 25. Appendicular FFM in kg measured by impedance (FFMi) in the fourcohorts and differences with DXA (FFMd). P-values of comparison with DXA by Student test and R2 values. From Jaffrin and Morel [35]

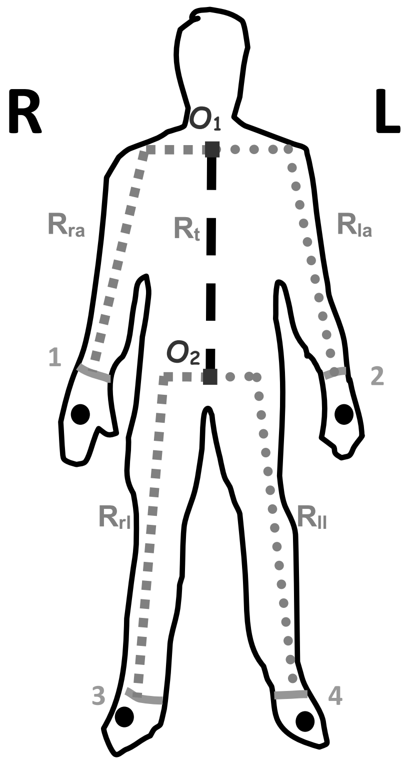

Fig. 13. Schematic of modified limbs resistances R. Rra =segment 1-O1, Rrl = segment 3-O2 etc.

Fig. 14. Electrode positions with eight electrodes medical impedance meters

		Right arm	Left arm	Right leg	Left leg
1st cohort Men n=85	FM, kg FMi-FMd p/DXA R^2	0.923 ±0.330 0.0002±0.173 0.814 0.78	0.864±0.320 0.0005±0.179 0.994 0.76	2.826 ±0.947 0.032±0.814 0.980 0.70	2.67 ±0.917 0.036±0.836 0.988 0.71
1st cohort Women n=85	FM, kg FMi-FMd p/DXA R^2	1.22 ±0.483 -0.009±0.203 0.967 0.85	1.19±0.485 -0.003±0.227 0.893 0.82	4.190±1.270 -0.001±0.728 0.990 0.71	4.00±1.15 -0.000 ±0.730 0.999 0.71
2nd cohort Men n=43	FM, kg FMi-FMd p/DXA R^2	1. 000±0.385 0.019±0.169 0.458 0.802	0.883±0.354 -0.044±0.188 0.128 0.752	2.874 ±1.093 0.026±0.592 0.774 0.708	2.716±1.03 -0.0146±0.562 0.866 0.709
2nd cohort Women n=44	FM, kg FMi-FMd p/DXA R^2	1.314±0.482 0.001±0.167 0.963 0.897	1.287 ±0.485 0.006±0.165 0.795 0.884	4.482±1.25 0.175 ±0.795 0.146 0.592	4.259 ±1.140 0.067±0.624 0.481 0.697

Table 26. Appendicular FM in kg measured by impedance (FFM_i) in the four cohorts and differences with DXA (FFM_d). P-values of comparison with DXA by Student test and R^2 values. From Jaffrin and Morel [35]

	Men 1st cohort N=85	Women 1st cohort N=85	Men 2nd cohort N=43	Women 2nd cohort N=44
Mean $FFM_{i,}$ kg p/DXA R^2	29.46±4.84 0.743 0.458	20.97±3.68 0.731 0.364	28.67±4.28 0.679 0.316	21.08±3.74 0.392 0.347
Mean $FM_{i,}$ kg p/DXA R^2	11.63±4.69 0.999 0.878	11.09±5.36 0.992 0.915	11.93±5.29 0.522 0.898	12.13±5.56 0.673 0.918
$FFM_{i,}$-$FFM_{d,}$ kg FM_i- $FM_{d,}$, kg	0.127±0.35 0.001±1.72	0.110±2.93 -0.002±1.62	-0.226±3.56 0.173±1.75	0.392±3.01 -0102±1.59

Table 27. Trunk FFM and FM by impedance for the four cohorts. Differences with DXA and p-valuesfrom Student's t-test. From Jaffrin and Morel [35]

It is interesting to see that right limbs have higher mean FFM than left ones. As expected, mean women FFM are 68% of those of men for both cohorts Although legs FFM_i are larger than arms FFM_i their difference with FFM_d are similar for men in the 1st cohort, while for women, these differences are definitely larger for legs. Mean FFM_i was slightly overestimated relatively to DXA in the 1st cohort, but was slightly underestimated in men of 2nd cohort. Since all p-values were all larger than 0.05, differences with DXA were not significant.

Mean FM in right limbs were about 6% higher than in left ones, but they were very close to those of DXA in the 1st cohort, as attested by high p values which varied from 0.814 to 0.999. This was to be expected as these equations were determined from 1st cohort data. In the 2nd cohort, differences between impedance and DXA were a little higher in men than in the 1st cohort, but p values were still larger than 0.697. Trunk fat mass FM_t was obtained using similar equations as for limb FM. For men it is

$$FM_{ti} = 0.7287FM_B + 0.2226\ BMI + 0.0564Age + 0.0318,\ R^2=0.89 \quad (37)$$

And for women,

$$FM_{ti} = 0.5730\ FM_B + 0.1298\ BMI + 0.0274Age - 6.454,\ R^2=0.92 \quad (38)$$

Table 32 shows that mean FM_i differences with DXA were very small in the 1st cohort, at 0.001 and 0.002 kg and R^2 coefficients were high in both cohorts, ranging from 0.878 to 0.918.

We have also compared FFM_{Bi} with the body FFM_{Bd} measured by DXA in **Table 28** for the two cohorts of 257 subjects. P-values are moderate, but differences with DXA are small.

		Men, n= 128		Women, n= 129	
		FFM_{Bi}	FFM_{Bi}- FFM_{Bd}	FFM_{Bi}	FFM_{Bi}- FFM_{Bd}
1st Cohort N=170	Mean± SD, kg p/DXA	61.13±7.13 0.208	-0.39±2.83	42.29±5.26 0.343	-0.27±2.66
2nd cohort N=87	Mean± SD, kg p/DXA	60.36 ±7.72 0.208	-0.52±2.66	42.09±4.74 0.329	-0.27±183

Table 28. Body FFM by impedance and DXA in men and women for the two cohorts. From Jaffrin and Morel [35]

Mean differences FM_B-FM_d with DXA were -0.39 kg for men and -0.27 kg for women in 1st cohort, against -0.52 kg for men and -0.27 kg for women in 2nd cohort. P-values were lower at 0.208 for men and 0.329 for women than for FFM and FM of trunk and limbs. These results confirm that it is possible to obtain reliable measurements of appendicular FFM and FM with eight contact electrodes by simply switching electrical connections in a system derived from an inexpensive FFI for home use. Mean differences between impedance and DXA were only 0.016 kg in arms and 0.0077 kg in legs which compares favorably with the results of Pietrobelli [31] who used a Tanita BC 418 8 electrodes and obtained mean FFM differences with DXA of 0.2 kg for arm and 0.35 kg for legs.

3.3.1 Measurements of body fluid volumes with FFI

Since TEFAL FFI uses a square electric signal, it can measure a low frequency resistance R_t at the top of the signal. Jaffrin and Morel [36] have investigated the feasibility of measuring ECW with a Tefal Bodymaster Vision by comparing with a multi-frequency Xitron Hydra 4200 medical impedance meter in a 1st group of 57 subjects. The Xitron measures the ECW resistance Re by extrapolation to zero frequency, which increases the resistance and their values were 11% higher in men and 20% higher in women than those measured by the Bodymaster at the top of its signal. This was expected as the Bodymaster resistance R_t could not be extrapolated to zero frequency. Differences between the mean FFI ECW (Ve_t) and the Xitron one (Ve) were 0.05±0.81 L in men and 0.02±0.49 L in women and not significantly different since p-values were 0.75 and 0.83, respectively. While there are several methods for measuring total body water (TBW) using bioimpedance analysis (BIA) from the wrist-ankle impedance at 50 kHz, the number of BIA methods from measuring extracellular water (ECW) from the same impedance is more limited. ECW and TBW measurements can be useful in several pathologies, such as hemodialysis [29], as the major part of water removed by ultrafiltration comes from ECW, or in cardiac disease, often leading to extracellular oedema. In addition, the difference between TBW and ECW yields the intracellular volume (ICW) which gives access to body cell protein mass BCM_{pro} [37] by

$$BCM_{pro}=0.3838\ ICW \tag{39}$$

At frequencies below 1 kHz, the current will not penetrate cell membranes and only circulates in the ECW. The BIS method [10] uses this property to calculate the ECW resistance R_e by extrapolating the impedance measured at various frequencies along a circle until the resistance axis, when it becomes a pure resistance at zero frequency (**Fig. 15).** The human body is then approximated as the sum of 5 cylinders (the limbs and the trunk) by multiplying the resistance-volume relationship for a single cylinder by a dimensionless shape factor K_B calculated from the length and perimeters of the limbs and the trunk to give the body resistance R

$$R = \frac{K_B \rho_a H^2}{V_B} \tag{40}$$

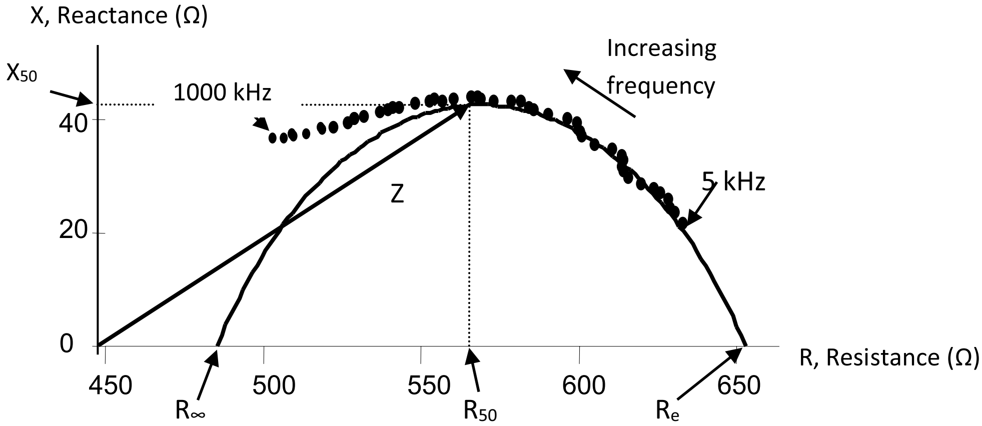

Fig. 15. Schematic of determination of resistances Re and R∞ by extrapolation in R-X plane

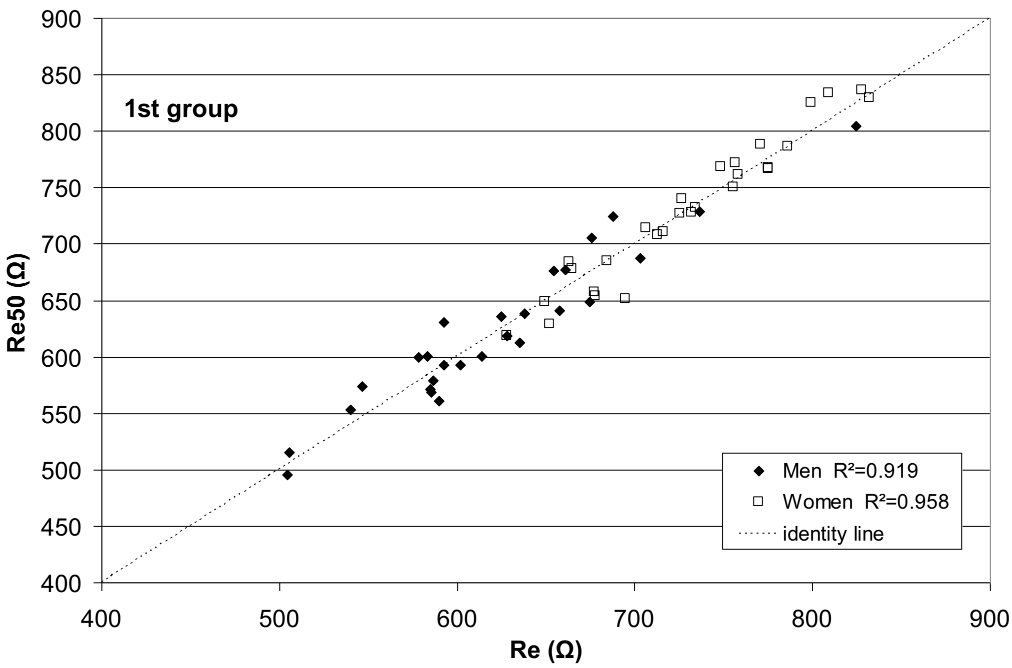

Fig. 16. Comparison of ECW resistances extrapolated from 50 kHz (Re50) with Re, extrapolated by the Xitron in the 1st group. From Jaffrin and Morel [36}

where V_B is the body volume, H the height and ρ_a the apparent tissue resistivity. De Lorenzo et al.[38] obtained a value of 4.3 for the shape coefficient K_B from statistical anatomical measurements in adults. The apparent tissue resistivity is given by Hanai's mixture conductivity theory [8], where c is the volume fraction of non-conducting tissues and ρ the resistivity of fluid inside tissues

$$\rho_a = \frac{\rho}{(1-c)^{3/2}} \tag{41}$$

At low frequency, c is equal to $1\text{-}V_e/V_B$, as only ECW is conducting and Eqs 40 and 41 lead to the following expression for ECW volume in L, where H is the height in cm, and W the body weight in kg

As expected, differences V_{e50}- V_{ex} calculated from Eqs 42 and 43 were very small for the 1st cohort using. However, when Eq.42 was replaced by Eq.43, differences V_{50}- V_{ex} were much higher at 0.24±0.49 L for men and 0.998±1.04L for women, versus 0.114±0.39 Land -0.06 ± 0.29 L respectively when using V_{e50}-V_{ex}. P-values were much lower at 0.078 for men and 0.016 for V_{50} versus V_{ex}, against 0.277 (men) and 0.393 (women) for V_{e50} versus V_{ex}. The mean and SD of R_{50}, measured by the Xitron at 50 kHz, those of R_e, extrapolated by the Xitron at zero frequency and their ratio R_{50}/R_e, are listed in **Table 29** for the 1st and 2nd groups of subjects. This table shows that values of R_e are higher than those of R_{50}, since the resistance decreases with increasing frequency. Mean values of R_{50}/R_e ratios obtained for the 1st group which are equal to 0.806 for men and 0.833 for women, were 622.4 Ω versus 623.4 for R_{ex}, in men, and 742.2 Ω versus 741.6 for R_e in women. These values of R_{e50} are not significantly different from those of R_e, with p-values of Student test equal to 0.794 for men and 0.831 for women.

	Men 1st group N=27	Women 1st group N=30	Men 2nd group N=15	Women 2nd group N=16
R_e ,Ω	623.4±68.7	741.6±69.7	623.6±67.8	733.8±75.5
R_{50}	501.7±56.0	618.3±63.6	498.6±58.0	616.2±65.6
$V_{ex,}$ L	17.88±2.3	13.01±1.35	18.19±1.97	13.52±1.42
V_{e50}, L	17.92±2.39	13.01±1.40	18.32±2.02	13.45±1.53
V_{e50}- V_{ex}	0.03±0.38	0.005±0.20	0.114±0.39	-0.06±0.29
pV_{e50}/V_{ex}			0.277	0.393
$V_{50,}$ L, Sergi	18.08±2.81	14.24±1.61	18.44±2.37	14.52±1.83
V_{50}- V_{ex}	0.19±0.55	1.23±0.29	0.24±0.49	0.998±1.04
$p\,V_{50}/V_{ex}$			0.078	0.0016

Table 29. Comparison of ECW volumes V_{e50} calculated by the 50 kHz-BIS method (Eq 36) and V_{50} calculated using V_{ex} measured by Xitron (Eq.35) in the same subjects. From Jaffrin and Morel [36]

The ECW volume is given by the Xitron using the BIS method for calculating the resistance R_e

$$V_{ex} = k_e\,(H^2 W^{0.5}/R_e)^{2/3} \tag{42}$$

where k_e is equal to 0.306 for men and 0.299 for women, while V_{e50} is given by

$$V_{e50}=k_e\,(bH^2W^{0.5}/R_{50})^{2/3} \tag{43}$$

The authors compared ECW volumes measured by Xitron using BIS method (V_{ex}) with those measured by the BodyExplorer at 50 kHz (V_{e50}) using Eqs 16 and 17. They also added an equation from Sergi et al [39].

$$V_{es}= 0.2\ H^2/R_{50} +0.005H^2/X_{50}+0.08W+1.86sex -3.3 \tag{44}$$

where X_{50} is the reactance and sex=0 for men and 1for women.

The comparison between ECW resistances extrapolated from 50 kHz (R_{e50}) with R_e extrapolated by the Xitron at zero frequency is shown in **Fig. 17** for the 1st group of men and women. There is a very good agreement between the two methods with correlation coefficients R^2 of 0.919 for men and 0.958 for women. **Fig. 18** compares the variation of V_{e50} and V_{es} (Sergi's Eq 44) given by the BodyExplorer versus V_{ex} from the Xitron men of 1st group. V_{e50} remains nearly equal to V_{ex} for the different subjects, while V_{es} overestimates V_{ex} by 1 to 1.3 L at high volume.

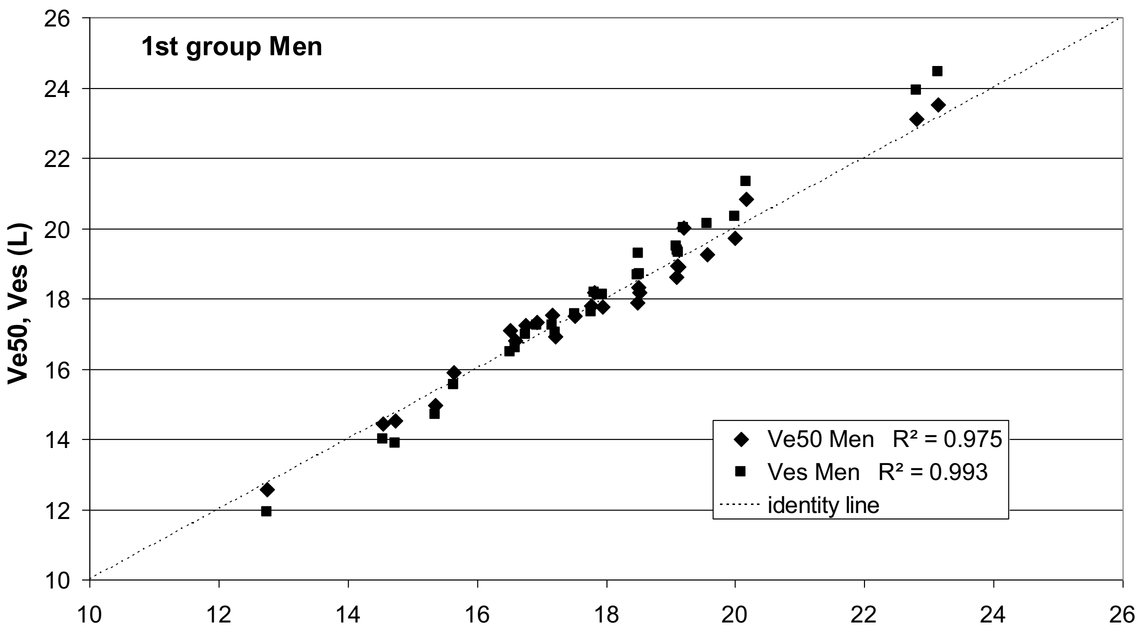

Fig. 17. Comparison of Ve50 and Ves with Vex from Xitron in men. From Jaffrin and Morel [36}

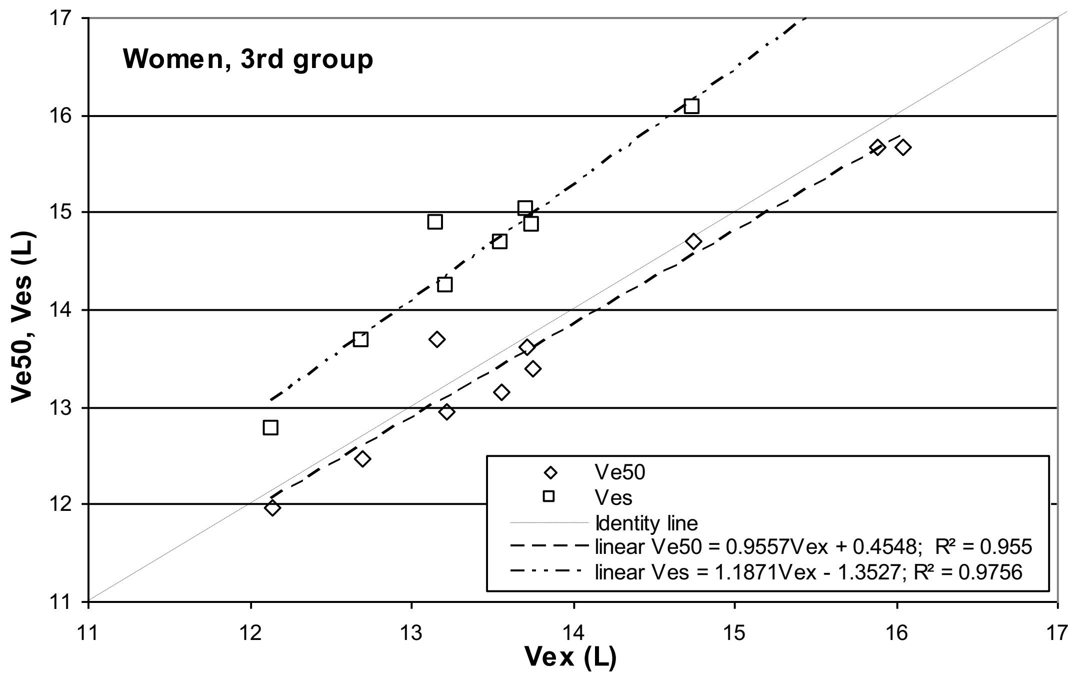

Fig. 18. Comparison between Ve50 and Ves (from BodyExplorer) and Vex (from Xitron) for women of 3rd group. From Jaffrin and Morel [36}

This could mean that, in the future, 50 kHz impedance meters could measure ECW and ICW using BIS method with nearly the same accuracy as multi-frequency impedance-meters, at least in subjects with normal ECW/ICW ratios. The validity of our method needs to be checked in subjects with abnormal fluid distribution, which may affect their mean TBW resistivity. It must be noted, however, that predictions of TBW loss in dialyzed patients by V_{tn} were found in good agreement with ultrafiltration data, although these patients have excess ECW before dialysis.

Jaffrin et al [40] have compared Organ method [34] and a segmental method with our new method which consists in solving a system of five equations for the resistances of limbs and trunk of a healthy group of 22 men and 26 women from their university. **Table 30** compares the resistances of both arms and both legs obtained from segmental measurements using shoulder, waist and foot electrodes with the 5-eqs and Organ method. As expected the segmental method gives smallest values for mean arm resistances at about 232 Ω against 250 Ω for 5-eqs and Organ method in men. In women, segmental arm resistances were smaller than with other methods, but right arm resistances were 8 Ω smaller than those of left arm. A similar trend was observed for 5-eqs and Organ method. The left arm resistance was 11 Ω higher that of right arm for the 5-eqs, while for Organ method, the mean left resistance was 7 Ω higher than that of right arm. This is due to the higher muscle mass in right arm which decreases the resistances. Mean segmental leg resistances in men were larger at 243 Ω, while for 5-eqs and Organ method, leg resistances were smaller than arm resistances. This is due to higher muscle mass in legs. Women had similar leg resistances for the segmental and Organ method, at 281Ω for right leg and 283.7 for the left one, while the 5-eqs method gave close to 274Ω for both legs. It results that Organ method overestimates arm resistances by 7.4% in men and 8% in women as compared to real segmental measurements. The 5-eqs method led to a slightly lower estimation at 6.8% and 5.8%. The advantage of Organ method is that it provides limb resistances without calculation, while the 5-Eqs computes them from linear equations, but gives closer results to segmental resistances. Neither 5-Eqs and Organ methods can precisely measure trunk resistance alone. **Fig. 19** plots the resistance-to-length ratio in right arm for women and men as a function of 1/BMI assuming that the mean muscular cross section would be proportional to the BMI. This ratio increases when BMI decreases and this ratio is higher in women because of their smaller muscle cross section than men. These ratios become equal when BMI has decreased to 16.7. The resistance-to-length ratio in right leg for women and men as a function of 1/BMI is plotted in **Fig. 20**. These ratios are smaller than for the arm, but with less difference between sexes due to closer muscle cross sections than in arms. The ratio variation with 1/BMI is similar for men and women. Another method for measuring head and trunk FFM consists in subtracting appendicular FFM from whole body one.

Men	Rra, Ω	Rla, Ω	Rrl, Ω	Rll, Ω	Rt, Ω
segmental	231±35	232±36	243±21	243±23.5	39.0±4.7.
5-Eqs	247±36.6	249±37	233±20	235±21.7	20.4±4.2
Organ meth	249±3752	250±37.6	237±20.8	239±23.3	
Women segmental	317±29.6	326±28.5	281±29.1	284±26.5	51.6±4.8
5-Eqs	336±29.8	347±28.2	274±29.7	283±28.5	22.4±2.7
Organ meth	343±30.2	350±29.0	281±29.7	283±28.5	

Table 30. Limbs and trunk resistances of limbs and trunk obtained from segmental, 5 equations and Organ's methods. Adapted from Jaffrin et al [40]

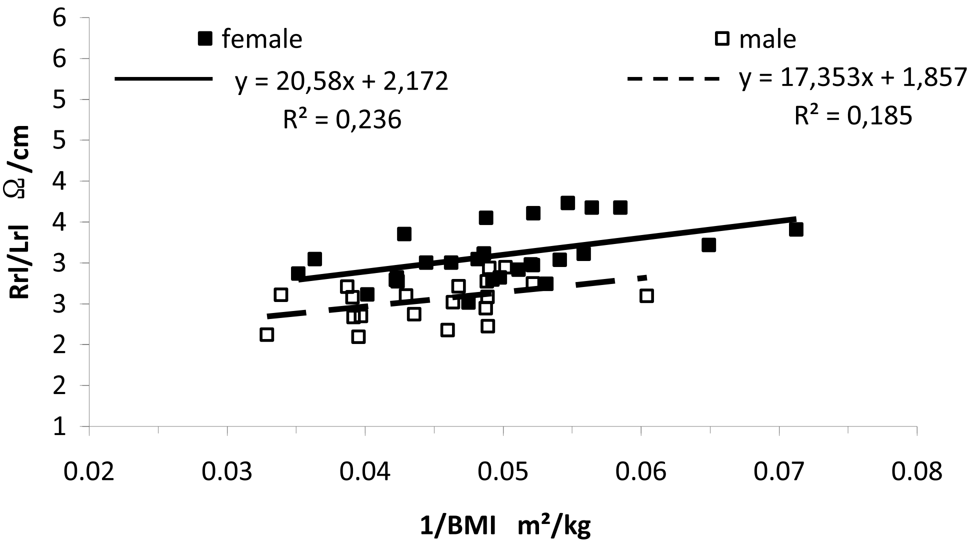

Fig. 19. Segmental resistance-to-length ratio in right arm for men and women as function of 1/BMI. From Jaffrin et al [40]

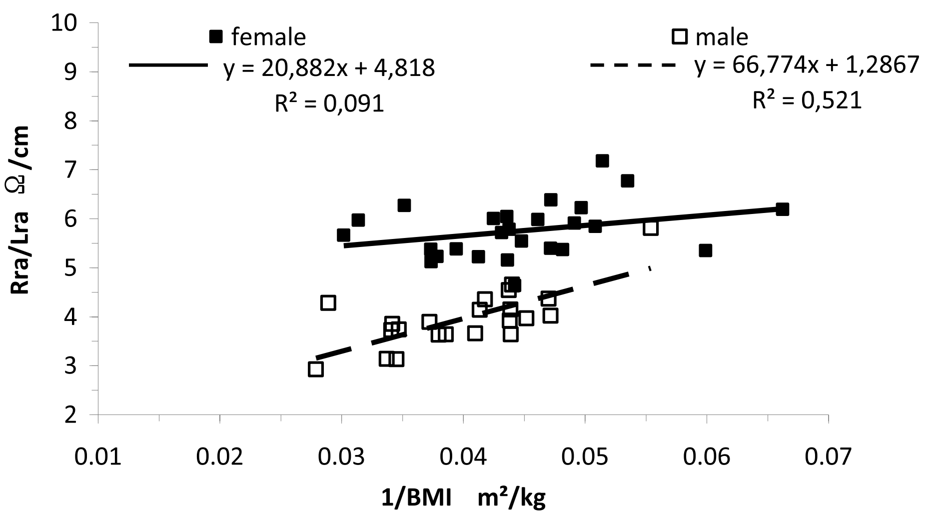

Fig. 20. Segmental resistance-to-length ratio in right leg for men and women as function of 1/BMI. From Jaffrin et al [40]

Morel and Jaffrin presented in [41] a method for extrapolating the TBW resistance R_{t50} from the resistance measured at 50 kHz (R_{50}). A DXA examination and impedance measurements were carried out in a 1st group of 57 healthy volunteers with a Xitron 4200 multi-frequency impedance meter, in order to determine their values of R_{t50} by comparison with resistances extrapolated at infinite frequency by the Xitron (R_∞). TBW volumes were calculated from the fat-free mass measured by DXA, assuming a hydration rate of 73.2%. The same protocol and calculations were also carried out on a 2nd group of 21 subjects for independent validation. Data of 1st group showed that values of R_{t50}, not significantly different from those of $R_{\infty,}$ could be obtained by dividing R_{50} by 1.231 in men and by 1.224 in women**.** According to BIS theory, the TBW resistance R_∞ is given as

$$R_\infty=\rho_\infty K_b H^2\, V_b^{0.5} V_{tn}^{-1.5} \qquad (45)$$

where ρ_∞ was the resistivity at infinite frequency which was determined from DXA measurements to be 104.3 Ωcm^{-1} for men and 100.5 Ωcm^{-1} for women and the body density D_b is equal to 1.05 kgL^{-1}. The TBW volume was calculated and is given by

$$V_{tn} = K_x(H^2W^{0.5}/R_\infty)^{2/3} \qquad (46)$$

with

$$K_x = 10^{-2}(4.3\, \rho_\infty)^{2/3} D_b^{-1/3} \qquad (47)$$

Thus Eq. (47) gives K_x equal to 0.576 for men and 0.562 for women with the selected units.

Applying this method to the 2nd group yielded also values of R_{t50} not significantly different from R_∞ and TBW volumes V_{t50} are obtained from R_{t50} by

$$V_{t50} = K_x\,(H^2W^{0.5}/\, R_{t50})^{2/3} \qquad (48)$$

V_{tn} obtained from Eq. 46 were not significantly different from those from those obtained from DXA in both groups, while the BIS method of Xitron underestimated the TBW volume V_{tx}.

A comparison with three BIA methods of TBW determination showed that our new method gave results in better agreement with TBW from DXA than the classical BIS method.

In conclusion, this review has shown that few authors have reported a good agreement for FM or %BF between BIA and DXA or other reference methods. It is also surprising that the Student T-test has not been used more often to evaluate the accuracy of BIA measurements. So we summarize a study made in our laboratory [42] of factors which may influence foot-to-foot resistance measurements with FFI and segmental measurements with eight electrodes devices.

4 Methods for increasing accuracy of foot-to-foot impedance meters

4.1 Impedance meters and podoscope

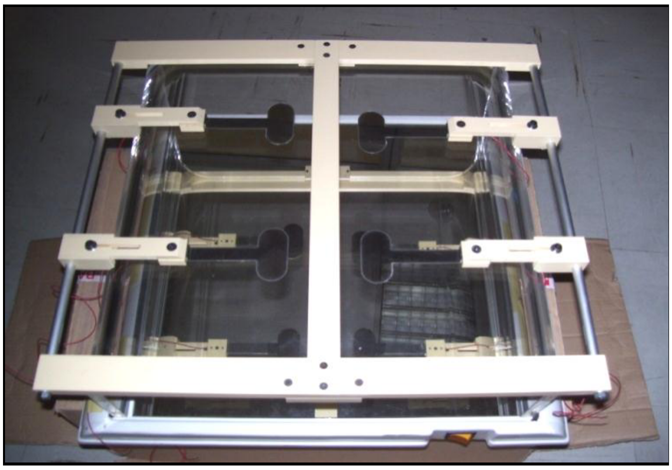

Fig. 21. Picture of podoscope with adjustable metal electrodes (in black)

A BodySignal Tefal FFI (Rumilly, France), was modified to display the high frequency resistance used to calculate FM and FFM, after entering height, weight, age and gender. A podoscope **(Fig. 21**) consisting in a thick horizontal glass plate supported by a metal frame was used. Flat aluminium electrodes of different sizes (16, 27, 38 and 56 cm^2) with rounded ends can be mounted on the glass plate and connected through wires to the FFI electronics which was modified to measure the resistance. A mirror and lamp under the glass plate permitted to take pictures of feet soles by placing the lens of a camera on the glass. Soles were first photographed without electrodes and another picture was taken with electrodes without changing feet position as shown in **Fig. 22**. The two pictures were superposed and the contact area of feet with electrodes was calculated in pixels by a Mathlab software. A calibration showed that 1 cm^2 corresponded to 860 pixels. Electrodes positions were adjusted both longitudinally and transversally to see their effect on the foot-to-foot resistance.

Fig. 22. Pictures of feet sole reflected by the podoscope mirror, a) without electrodes, b) with 27 cm_2 electrodes

4.2 Protocol, subjects and statistical analysis

Foot-to-foot measurements were carried out on 35 healthy graduate students and staff from our university who gave informed consent, and the protocol was approved by the Ethical Committee. Subjects were asked to empty their bladder before measurements and to wipe off the sweat under their feet before stepping on electrodes and were divided in groups for the various tests. Mean values and SD of resistances, regression lines and correlation coefficients R^2 were calculated for every test.

4.3 Results

4.3.1 Variation of body resistance with electrodes area

These measurements were carried out on nine subjects using 27 cm^2 voltage electrodes mounted on the podoscope connected successively to the electronics of the BodySignal [42]. The surface area of current electrodes was set successively at 16, 27, 38 and 56 cm^2. **Table 31** shows the mean resistances R of BodySignal and their SD for the nine subjects. **Fig. 23** shows the variation of foot-to-foot resistance of a female subject with contact area of current electrodes using two Tefal FFI, a BodyUp and a BodySignal. The resistance was about 30 Ω higher for the BodyUp, but this was probably due to in part to a different feet position on the scale. When current electrodes area increased from 16 cm^2 to 56 cm^2 with 27 cm^2 area voltage electrodes, the mean resistance of subjects decayed linearly in **Fig. 24** from 519 to 498 Ω due to a decrease in contact area between soles and electrodes which decreased the current at constant voltage. The mean resistances of the BodyUp were only 10 Ω higher than that of BodySignal, due to averaging between subjects.

Electrode size, cm^2		BodySignal, N=9			Electrode size, cm^2		BodySignal N=10		
Voltage, V	Current, A	Mean,R, Ω	SD,Ω	Scc, cm^2	Voltage, V	Current, A	Mean R, Ω	SD, Ω	Svc, cm^2
27	16	519.3	59.5	22.5	16	38	521.0	68.8	27.1
27	27	509.8	58.2	36.0	27	38	522.2	52.3	43.1
27	38	502.6	58.9	53.8	38	38	514.1	72.9	63.1
27	56	497.8	59.9	67.3	56	38	511.1	88.5	52.5
mean		507.6	59.1	44.9			517.1	70.6	46.4

Table 31. Variation of mean resistance with contact area of current electrode with feet (left) and with contact area of voltage electrodes (right) using the BodySignal. Adapted from Bousbiat et al [42]

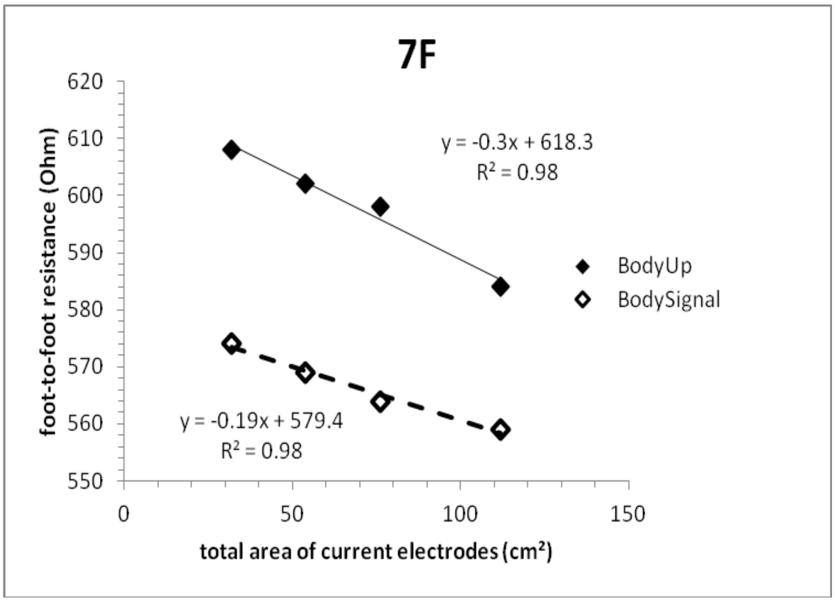

Fig. 23. Variation of resistance with total area of current electrodes for a female subject 7F. From Bousbiat et al [42]

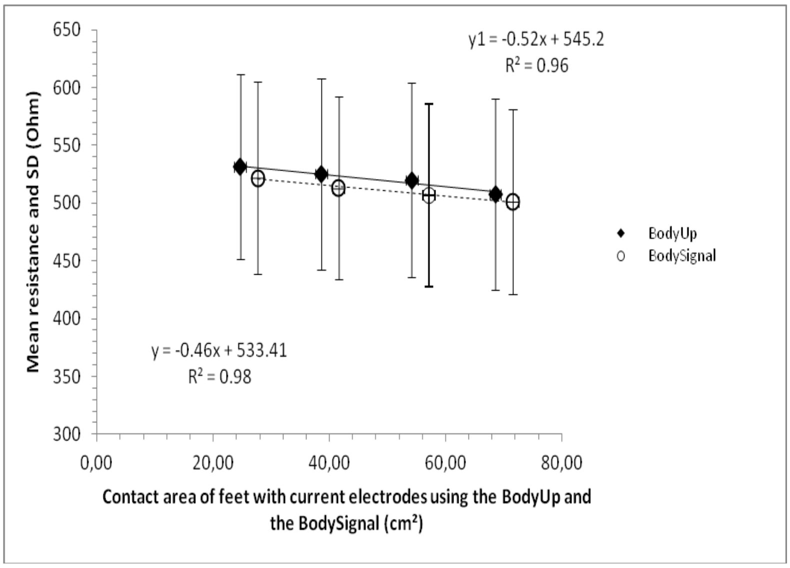

Fig. 24. Variation of mean resistance and SD with contact area of feet with current electrodes using the BodySignal and the BodyUp for 9 subjects. From Bousbiat et al [42]

A similar test was carried out using the BodySignal on the same group plus an additional subject, using current electrodes of 38 cm^2 area and varying voltage electrodes of 16, 27, 38 and 56 cm^2. Data are given in the right columns of **Table 31.** When voltage electrode area was increased from 16 to 56 cm^2 with 38 cm^2 current electrodes, the mean resistance decayed from 522 to 511 Ω, as seen in Table 31 and **Fig. 25**. The mean contact area of heels and voltage electrodes was slightly larger than for current electrodes.

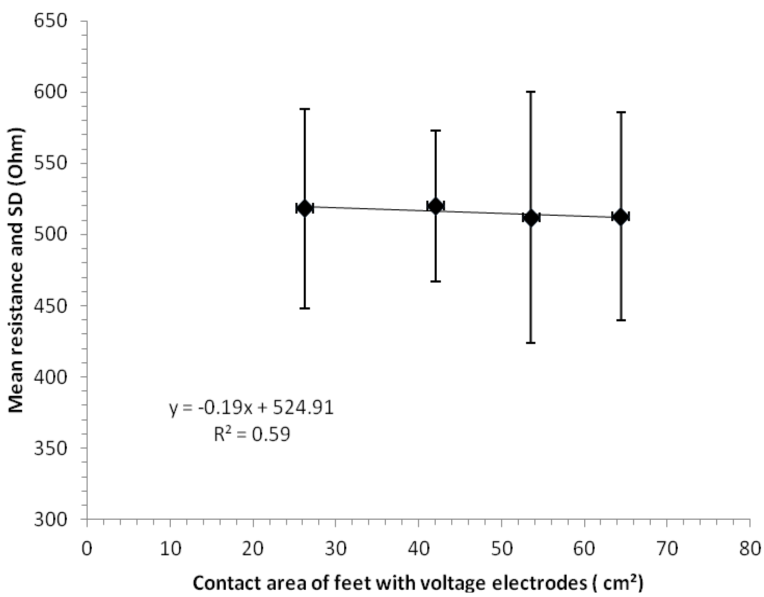

Fig. 25. Variation of mean resistance and SD with contact area of feet with voltage electrodes using the BodySignal for 10 subjects. From Bousbiat et al [42]

4.3.1 Effect of feet size and voltage electrode configurations on mean foot to foot resistances and measurement reproducibility

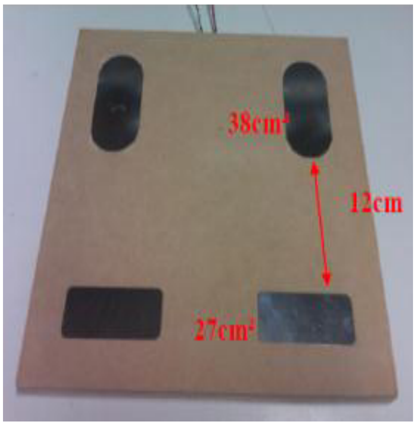

Fig. 26. Wood prototype with longitudinal current electrodes and transverse voltage electrodes to optimize feet position

These tests were carried on four men and four women using two commercial TEFAL FFI, a BodySignal with a round plate and four identical circular shaped electrodes, and a Withings (Fig. 3) with four large and identical square electrodes, both connected to the electronics of the BodySignal. A FFI prototype, also fabricated by TEFAL consisted in a wood plate with longitudinal current electrodes of 38 cm² area and transverse voltage electrodes of 27 cm² area (**Fig. 26**) connected to the electronics of a BodySignal. Each subject repeated the test ten times witheach impedance meter by stepping up and down the scale, first without constraint (free heel position) and another ten times with his heels against a small rod (fixed heels). Mean resistances and SD for all subjects given by each FFI are listed in **Table 32.** A small SD corresponds to a good reproducibility. Mean resistances were lowest with the wood prototype using transverse electrodes, at 456 Ω for men and 571 Ω for women with free heels. Mean Withings resistances with free heels were largest (493 Ω in men and 620 Ω in women) due to its large electrodes areas as resistances of the sole skin were higher. Resistance reproducibility was best for the wood FFI with transverse voltage electrodes in fixed heels position with a small SD of 0.47% in men and 0.40% in women as subjects could accurately place their heels on electrodes. Highest SDs were found with the Withings in free heels position, at 1.32% for men and 1.34% for women. Fixed heels position improved little the reproducibility by decreasing SD at 1.11% (men) and 1.14% (women). With the BodySignal, mean resistances were significantly smaller in fixed position at 463 Ω for men and 583 Ω for women, respectively smaller than in free position by 12.6 Ω in men and 6.9 Ω in women. This may be due to its circular electrodes as a small change in feet position could greatly modify the contact area between feet and electrodes. The reproducibility in free position was 1.26% in men and 1.30% in women, only slightly smaller than those of Withings, 1.32% and 1.34%, but with fixed heels the BodySignal SD was 0.96% in men and in women against 1.11% and 1.14% in women for the Withings.

FFI	Feet position	Men, Shoe Size>41			Women, Shoe size<37		
		Mean R, Ω	SD Ω	SD %	Mean R, Ω	SD Ω	SD %
BodySignal	Free	475.5	6.02	1.26	590.4	7.67	1.30
BodySignal	Fixed	462.9	4.43	0.96	583.5	4.09	0.96
Withings	Free	493.2	6.62	1.32	620.5	8.31	1.34
Withings	Fixed	490.2	5.49	1.11	622.8	7.06	1.14
Transverse electrodes 27 cm2	Free	456.3	4.09	0.89	570.7	5.15	0.90
Transverse electrodes 27 cm2	Fixed	457.1	2.16	0.47	577.4	2.31	0.40

Table 32. Effect of electrodes and scale design on foot-to-foot resistance measurements with three FFI, a BodySignal, a Withings and a Tefal prototype with transverse voltage electrodes.

5 Discussion

5.1 Effect Of Resistance Errors On FM And FFM Determination.

In order to evaluate the error in FM caused by inaccurate resistance measurements, we have selected a group of four men and four women with various BMI who had their FM measured by DXA (FM_d). We included one man and one woman with high BMI, respectively 38.6 and 49.2 kg m^{-2}, other subjects having BMI ranging from 19 to 27kg m^{-2}. Their FM, denoted FM_{i1} were calculated from their foot-to-foot resistance R_1 using sex specific equations determined from DXA data on a cohort of 170 healthy subjects [28] which were, for males

$$FM_{i1}\ (kg) = -0.3396\ H^2/R_1 + 0.686\ W + 0.1022\ Age - 17.52 \quad (48)$$

And for female subjects

$$FM_{i1}\ (kg) = -0.223\ H^2/R_1 + 0.7645\ W + 0.0574\ Age - 18.45 \quad (49)$$

These FM_{i1} were calculated from the resistances R_1, H, W, while FM_{i2} were calculated after subtracting 30 Ω from each resistance. Results of FM_i changes are displayed in **Table 33**. This resistance reduction decreased the mean FM_i in men from 19.06 kg to 17.71kg, while in women, the mean FM_i was reduced from 25.32 kg to 24.67. FM_{i2} were smaller than FM_{i1} for each subject. Equations 38 and 39underestimated mean FM_{i1} relatively to DXA by -1.94 kg in men and by-1.98 kg in women. FM_{i2} increased this underestimation to -3.29 kg in men and to -2.17 kg in women, so it is important to make accurate resistance measurements to calculate accurate FM_i. A 30 Ω resistance variation can easily occur during measurements with FFI.

Mean values	R_1 ,Ω	R_2, Ω	FM_d kg,	H, cm	W, kg	Age yr	BMI kgm^{-2}	FMi_1, kg with R_1	FMi_2, kg with R_2	FMi_2-FMi_1 kg
Men	504.2	474.2	20.9	178	82.3	25.5	25.7	19.06	17.71	-1.35
Women	536.2	506.2	27.3	162	69.8	28	27.2	25.32	24.67	-0.65
All	520.2	490.2	24.1	170	76.0	26.7	26.4	22.19	21.19	-1.0

Table 33. Effect of a resistance decrease of 30 Ω on mean values of FMi calculated by BIA, on four men and four women. Values of FMd by DXA and subject mean characteristics.

In [42] we reported that a 5 cm backward move of the feet will increase the body resistance R as it increases the current path on the sole from voltage electrode, while a 5 cm forward move will decrease R as it decreases the current path. Changes in resistances are listed in **Table 34** using a BodySignal and a BodyExplorer impedance meter on 10 subjects, both connected to the same electrodes on the podosope. It can be noted that a backward move of only 5 cm will increase mean R_1 of BodySignal by 36.9 Ω which may decrease FM by about 1.67 kg. The mean R_2 of BodyExplorer was 523 Ω against 511 for the BodySignal, but its increase was only 26.9 Ω. Forward moves decreased the resistances but by smaller amounts, respectively -16.6 and -12.2 Ω.Although our group of subjects was small, the results are still interesting.

	Normal position		Feet moved back 5 cm		Feet moved forward 5 cm	
N=10	BodySignal R_1 ,Ω	BodyExplo R_2, Ω	BodySignal Δ R_1 ,Ω	BodyExplo Δ R_2 ,Ω	BodySignal Δ R_1 ,Ω	BodyExplo Δ R_2 ,Ω
Mean	511.2	523.3	36.9	26.9	-16.6	-12.2
SD	61.7	60.0	16.3	12.1	9.7	4.6

Table 34. Variations of mean resistances and SD with 5 cm feet displacement. From Bousbiat et al [42]

5.2 Reproducibility Of Resistance Measurements

These tests were carried out on 14 subjects, 6 males and 8 females, with voltage electrodes of 16 cm^2 area and three types of current electrodes of 27, 38, 56 cm^2 area, connected to the electronics of a BodySignalV2. A 4th test was made with four 56 cm^2voltage and current electrodes to see the influence of voltage electrode size. Each subject was asked to repeat his measurement by stepping up and down 10 times from the podoscope without receiving particular instructions. A synthesis of these tests is given in **Table 35**, which lists mean values of resistances and SD for the 14 subjects and for each combination of electrodes tested. A small %SD corresponds to a good reproducibility, and it depends to a large extent on the placement of feet on the electrodes. The BodySignal V2 had a mean SD of 0.67%, but individual SD of subjects can be higher, and reached a maximum of 0.72%. Reproducibility will be of course high if the subject places his feet in a consistent way on the electrodes.

Voltage elec cm^2	Current elec cm^2	R_1, Ω	SD, Ω	SD%
27	27	510.7	3.72	0.73
27	38	509.5	3.24	0.64
27	56	506.5	3.72	0.72
56	56	509.7	3.13	0.61
Mean values		509.1	3.45	0.67

Table 35. Mean values and SD in Ω and % of mean resistances of 14 subjects during reproducibility tests for each electrode configuration using the BodySignal connected to the podoscope. From Bousbiat et al [42]

To separate the contribution of electronics to resistance variability from that of electrodes, reproducibility tests were also carried out on four subjects using the BodySignal V2 and a BodyExplorer connected to the podoscope equipped with 38 cm^2 current electrodes and 27 cm^2 voltage ones. These tests were performed by switching on and off the devices, without stepping down and changing feet position. In these tests, resistances decayed with time by less than 2 Ω as seen in **Fig. 27**, for a female subject and other subjects gave similar results. This small decay was probably due to fluid drainage by gravity into the calves which have a smaller cross section than the thighs and the calves' resistance decreased more than the thighs resistance increased.

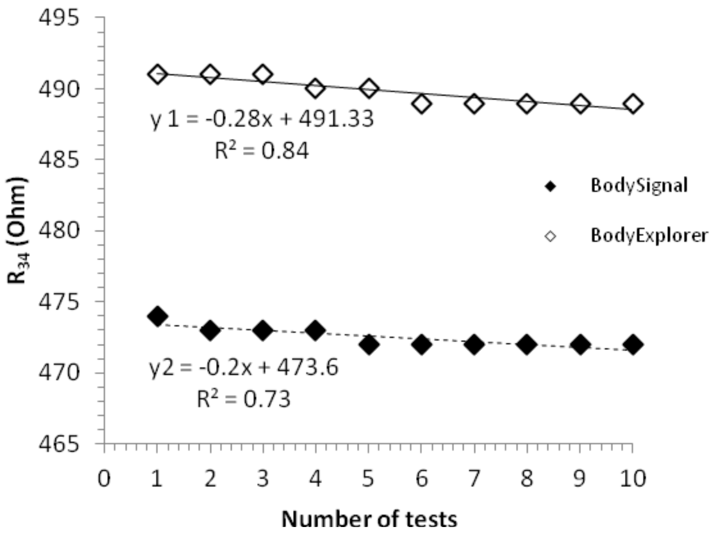

Fig. 27. Variation of resistances during 10 successive measurements on one subject without changing feet position. From Bousbiat et al [42]

Another reason may be the build-up of sweat under the sole that decreases the feet contact resistance with electrodes. Mean resistances and their SD are listed in **Table 36** which shows that resistances, measured in the same subjects with the same electrodes by the BodySignal V2, were 10.5% smaller than those of the Body Explorer, confirming BodySignal V2 higher frequency. Mean SD were 0.67 Ω for the BodySignal V2 and 0.77 Ω for the BodyExplorer, or 0.15% for both devices as the BodySignal V2 resistance was slightly lower. The SD on 4th line corresponds to SD between the 4 subjects. The fifth line indicates that the %SD is lower at 5.77% for the BodySignal V2 versus 9.28% for the BodyExplorer. This experiment confirms the excellent reproducibility of both electronics as, in Fig. 27, the resistances remained constant when fluids have stabilized after the fifth or seventh test and that the major part of resistance SD in **Table 36** is due to differences in feet position.

N=4	BodySignal V2			BodyExplorer		
	R_1, Ω	SD, Ω	SD %	R_2, Ω	SD, Ω	SD %
Mean	440.2	0.67	0.157	487.4	0.77	0.155
SD , Ω	25.4	0.23	0.06	45.24	0.26	0.04
SD%	5.77			9.28		

Table 36. Mean resistances in Ω and SD in Ω and % during reproducibility tests on 4 subjects without moving feet on the podoscope equipped with 38 cm² current electrodes and 27 cm² voltage ones, using the BodySignal V2 and the BodyExplorer. From Bousbiat et al [42]

To facilitate heels position on voltage electrodes, we have replaced short longitudinal voltage electrodes by rectangular ones mounted transversally to the feet, so that they remain well visible on the side of each foot by the subject. Tests were carried out on two womenand three men. **Table 37** shows mean resistances of each subject and their SD in Ω and % during 10 tests. The mean SD for the 5 subjects was 0.39%, against 0.67 % in Table 37 for similar tests with longitudinal voltage electrodes. Mean resistances were slightly larger with 27 cm^2 voltage electrodes, 472 Ω versus 479 Ω and their SD lower, respectively 1.86 versus 2.21 Ω.

	Current 38 cm^2,Voltage 16 cm^2			Current 38 cm^2,voltage 27 cm^2		
subject	Mean R, Ω	SD, Ω	SD,%	Mean R, Ω	SD, Ω	SD,%
1F	472.1	2.26	0.48	483.4	2.01	0.42
5F	512.6	1.65	0.32	511.7	2.16	0.42
1M	453.6	1.65	0.36	462.1	1.85	0.40
10M	433.1	2.38	0.55	437.3	1.25	0.9
12M	490.0	1.65	0.63	498.9	2.02	0.41
Mean all	472.3	2.21	0.47	478.7	1.86	0.39

Table 37. Reproducibility of resistance measurements using transverse voltage electrodes of 16 cm^2 and 27 cm^2 with 38 cm^2 current electrodes. From Bousbiat et al [42]

5.3 Effect of feet position and leg flexion on resistance and reproducibility

In order to see if reproducibility could be improved by a more precise positioning of feet on electrodes, similar tests as in section 5.2 were made successively without constrain (free heels) as previously, and after fixing on the podoscope a small rod behind each voltage electrode to control heel position. These tests were performed with the BodySignal V2, using 16 cm^2 voltage electrodes and 38 cm^2 current ones on another group of 14 subjects. We have also investigated the effect of 1.5 cm forward and backward displacements of heels relatively to voltage electrodes by moving the small rods accordingly, each test being repeated ten times. Finally, we have compared resistances measured in normal standing position (R_n) with those (R_c) measured with the knees slightly bent, in order to contract leg muscles. Mean values and SD of these resistances for the 14 subjects are listed in **Table 38**.

N=14	Free heels	Fixed heels	Forw 1.5 cm	Backw 1.5 cm	R_n	R_c	R_n-R_c
Mean R, Ω	494.3	490.1	485.8	492.3	493.0	465.5	27.5
SD, Ω	4.36	2.56	2.27	1.86	3.16	3.94	8.5
SD %	0.88	0.52	0.47	0.37	0.63	0.81	

Table 38. Mean values and SD of mean resistances of 14 subjects during reproducibility tests with various heel positions using 16 cm^2 voltage and 38 cm^2 current metal electrodes. Free heels: without constraint. Fixed heels: using rods behind each heel: R_n resistance in normal standing position: R_c resistance with leg muscles contracted by flexing the knees. From Bousbiat et al [42]

It can be seen that the mean resistance was also slightly higher for free heels since, if heels were moved backwards relatively to voltage electrodes, the length of current path under the feet increased. The reproducibility was better when rods were used (fixed heels), as SD was 0.52% instead of 0.88% for free heels. This explanation is confirmed by the 4rd and 5th columns of Table 38 which shows that moving forward the heels by 1.5 cm decreases the mean resistance by 4.3 Ω as compared to fixed heels value, while a backward move increases it by 2.1 Ω. These changes are of course smaller than those reported in section 4.4 with a ±5 cm displacement. Contracting the muscle legs reduces the mean resistance by 27.5 ± 8.5 Ω. This is because the muscle contraction pushes body fluids into the calves which have a smaller cross section than the thighs, decreasing calf resistance more than increasing that of the thigh. A similar decrease of resistance with time was observed in Fig. 27 until test Nb 8 under the action of gravity in successive measurements made by switching on and off the electronics without changing feet position.

5.4 Effect of a resistance variation on the determination of body fat measurement

In order to evaluate the error in FM caused by a resistance variation, we have selected a group of four men and four women with various body mass index (BMI) who had their FM measured by DXA (FMd). Their FM (denoted FMi) were calculated from their foot-to-foot resistance R using sex specific equations determined from DXA data on a cohort of 170 healthy subjects [28]. These equations, deduced from those of FFMi are l.5]. These equations, deduced from those for the fat-free-mass (FFMi) were

For women: $FMi = W - FFMi = -0.223\ H^2/R + 0.7645W + 0.0574\ Age - 18.45$ (50)

For men: $FMi = -0.3396\ H^2/R + 0.686W + 0.1022\ Age - 17.52$ (51)

where H is the height in cm, age is in years and W is the weight in kg.

We then recalculated the FMi of these eight subjects by adding and subtracting 6 Ω from the normal resistance using equations (50) and (51). The FMi variation (ΔFMi) caused by a 12 Ω resistance variation is plotted in **Fig. 28** for these subjects as a function of their normal resistance. These FMi variations decrease when resistance increases, which corresponds to a decrease in BMI. Complete data are given in **Table 39.** In men, the smallest FMi variation of 0.46kg corresponds to the smallest BMI (20.9 kg/m^2) and largest resistance (subject 3H) while the largest variation (1.4 kg) was for subject 4M with largest BMI and smallest resistance. This was expected since the percentage of resistance variation was smallest in subject 3M with the highest resistance and largest for male subject 4M. However, it is interesting to note that the FMi variation in % was smallest in subject 4M at 3.7%, although he had the largest variation in kg. Results are similar in women as subject 2F with the smallest BMI had the smallest FMi variation (0.27 kg) and the largest resistance and subject 4F, with highest BMI and smallest resistance, had the largest FMi variation (0.63 kg) and the smallest BF % (1.0%). It is encouraging that the mean values of ΔFMi for a 12 Ω resistance variation were only 0.89 kg or 5.9% men and 0.48 kg or 2.45% for women although there was a subject with very large BMI and fat mass in each group.

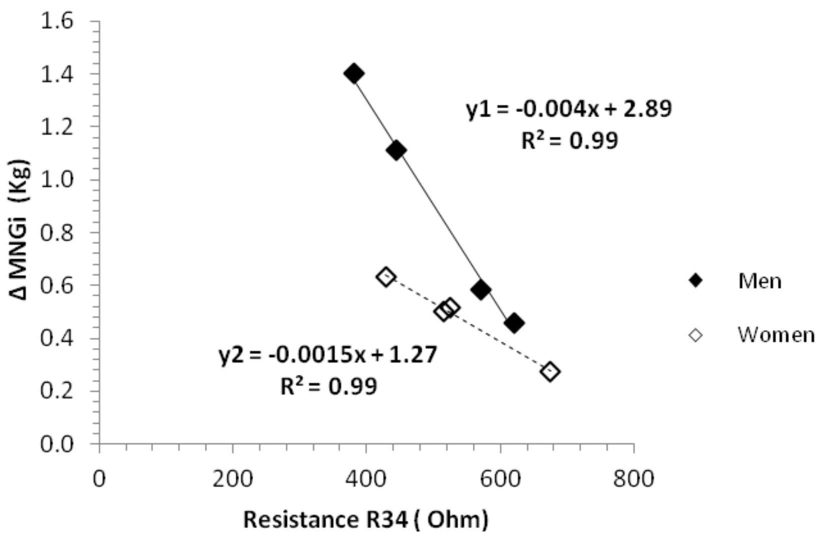

Fig. 28. Variation of mean FMi calculated by impedance in eight subjects produced by a 12 Ω resistance variation as function of their foot-to-foot resistance R34. From Bousbiat et al [42]

Subject	R, Ω	FMd kg	H, cm	W, kg	BMI kg/m2	FMi kg	FMi-FMd kg	ΔFMi kg	ΔFMi %
1M	571	14.3	175	64.2	21.0	10.4	-3.9	0.58	5.5
2M	444	10.0	188	78.9	22.3	11.8	1.8	1.11	9.4
3M	621	10.0	169	59.7	20.9	9.2	-0.8	0.46	5.0
4M	381	49.3	181	126.6	38.6	44.1	5.2	1.40	3.7
1F	525	13.4	170	61.2	21.2	18.2	4.8	0.52	2.8
2F	675	15.9	159	4705	18.8	11.6	-4.3	0.27	2.3
3F	516	17.7	165	5309	19.8	13.4	-4.3	0.50	3.7
4F	429	62.1	154	116.7	49.2	63.7	1.6	0.63	1.0
Mean	520	24.1	170	76.0	26.4	22.8	0.012	0.68	4.2

Table 39. Table 39. Effect of a resistance variation of ± 6 Ω on values of FM calculated by impedance (FMi) on four males (M) and four females (F) and comparison with DXA (FMd). ΔFMi= $FM-_6$-$FM+_6$ where $FM-_6$= FMi at R-6 Ω and $FM+_6$= FMi at R+6 Ω. From From Jaffrin and Bousbiat [43]

Among the quoted references, nine [7, 13, 16, 19, 22 for Asians, 24, 27, 31 for trunk and head, 33 for whites and blacks men and Hispanics women] reported a general FM under-estimation as compared to DXA or UW and 4C models, seven [20, 22 for Caucasians and blacks, 25 for boys and girls, 26, 31 for arms, 32 for obese, and 33 for Hispanics men] reported an overestimation in obese subjects or to arms or legs. The accuracy of FFI depends also upon the scale design. Unlike adhesive electrodes which are fully standardized and accurately placed on ankles and wrists, the accuracy of plantar electrodes is conditioned by electrode size and design and by feet position on electrodes.

6 Conclusion

There are two types of body composition measurements. Those, made with medical impedance meters in supine position with disposable adhesive electrodes pasted on the right hand and foot, can use equations from the literature to calculate FFM and FM from the resistance because of electrodes and electronic standardization. The situation is different for FFI as there is no standardization of plantar electrodes and body scale design. It was shown in section 5 that the foot-to foot resistance depends upon electrodes area and design. Jaffrin et al [**35**] observed that the mean value of ECW resistance R_{et} measured by a Tefal Bodymaster was smaller than the ECW resistance measured with a Xitron Hydra 4200 in supine position by 11% in men and by 20% in women. This was due to shorter current paths limited to the legs and waist for the Tefal and the decrease in leg resistance as ECW accumulates in the legs by gravity. Multi frequency impedance meters can accurately measure TBW and ECW and obtain ICW by difference.

An important question is whether FFI with four plantar electrodes are as accurate for measuring body composition as medical impedance meters with standardized electrodes pasted on a hand and foot. It is true that a medical impedance meter measures the sum of arm trunk and leg resistance while FFI measure only the legs resistance and the trunk width and need software adapted to their electrodes and body scale. But Bousbiat et al [28] have compared the accuracy of using foot-to-foot resistance R_{34} with that of hand-to-foot R_{13} using the same electronics and the same five equations (K_1, K_2, K_3, L_1, L_2) for calculating differences between FFM_i and FFM_d by DXA. The hand voltage electrodes had a similar area as those of the FFI. Mean values of FFM_d of 2nd cohort were 42.37±5.07 kg for women and 60.55±7.77 kg for men. Table 19 shows that, for the 2nd cohort (validation) of women, the mean differences FFM_i-FFM_d for the 5 equations was 0.517 kg for R_{13} and the mean p-value was 0.125, while with R_{34} the mean FFM_i-FFM_d was 0.196 kg, much less than for R_{13} and the mean p-value was 0.665, much higher than R_{13}. Table 20 shows that, for the 2nd cohort of men, the mean differences FFM_i-FFM_d for the 5 equations was 0.180 kg for R_{13} and the mean p-value was 0.661, while with R_{34} the mean FFM_i-FFM_d was 0.132 kg, again less than with R_{13} and the mean p-value was 0.727. The higher p-values and lower FFM differences corresponding to the use of R_{34} relatively to R_{13} confirm the superiority of R_{34} because of the absence of arm resistance.

New FFI and 8-electrodes impedance meter offer interesting opportunities, not only for the general public, but also for the medical community. Their main advantage is that they permit rapid impedance and weight measurements in standing position with reusable electrodes. Their weak point is that their accuracy and reproducibility depends upon the design of body scale and electrodes, which should not be dictated merely by esthetic considerations. It is necessary to design FFI electrodes which facilitate the reproducibility of resistance measurements. It is also important that current electrodes must be long and placed longitudinally in order to accommodate different feet sizes while keeping a sufficient feet-electrode contact area. Voltage electrodes, on the contrary, can be small and round as in Tanita FFI, but it may be preferable to have narrow electrodes placed transversally as in Fig. 26, so that the user can see them and locate his heels precisely on them. In case of round voltage electrodes, mounting semi-circular arches behind the heels will help placing them accurately. This design should increase the accuracy and reproducibility of resistance measurement. FFI should use specific softwares, especially designed for them, which must be modified in case of changes in electronics and electrode design. Since FFI are now used worldwide, FM and FFM equations should be adapted to specific ethnics.

The additional advantage of 8-electrodes FFI is that their software permits them to rapidly measure limbs and trunk resistances and to deduce corresponding FM and FFM. If Biospace and Jawon 8-electrodes devices are much more expensive than 4-electrodes FFI, the Omron HBF 511, and Tanita BC545 N and BC601 are quite reasonable. They can also measure whole body resistance using plantar electrodes or hand and foot electrodes and they can calculate whole body FM by summing limbs and trunk FM obtained from segmental measurements. Lim et al [25] considered that the multi-frequency InBody 720 increase the accuracy of impedance measurements by dividing the body in four limbs and trunk with head as body geometry is more respected than with an extrapolation of the lower limbs to the complete body and obtained a mean FM difference between the Inbody and DXA of 0.9 kg for boys representing about 11% of FM_d and 0.8 kg for girls representing 10% of FM_d.

7 Summary

The measurements of body composition, fat mass, fat-free mass, muscle mass, total body water, extra and intracellular waters are important to evaluate the health. These measurements can be made with simple devices, called impedance meters which provide the hand-to-foot resistance or the foot-to-foot one. The knowledge of these resistances together with body height, weight and age permit to calculate fat mass (FM), or fat-free-mass (FFM), total body water (TBW), extracellular (ECW) and intracellular water (ICW). The 1st and 2nd chapters present the various types of medical impedance meters used in supine position with four adhesive electrodes on hand and foot and foot-to-foot ones (FFI) used in standing position with plantar reusable electrodes which generally cost less than 90 €. The introduction in 2003 of Japanese and Korean eight electrode impedance meters with four plantar and four hand electrodes permit to measure limb FM and FFM in standing position in a single operation. The 3rd chapter presents the main applications of impedance meters described in the relevant literature, which cover FFM, FM, %BF, TBW, ECW and ICW, together with measurements by Dual X-Ray absorptiometry which can be considered as a reference method. The 4th chapter describes methods for increasing the accuracy of FFI by optimizing electrodes design.

Current electrodes should be disposed longitudinally on the scale to accommodate various feet sizes, but voltage electrodes should be narrow and disposed transversally to the feet so that the user can place his heels precisely on voltage electrodes to minimize the resistance and maximize the reproducibility. The discussion in the 5th chapter evaluates the error in FM caused by inaccurate resistance measurements. A diminution of 30 Ω from the mean resistance decreases the FM by -1.35 kg in men and of -0.65 kg in women. The 6th chapter concludes that the advantage of FFI over medical devices, is that they permit rapid impedance and weight measurements. They are very easy to use and their prices are very reasonable. But their design should facilitate the correct position of toes on current electrodes and of heels on voltage electrodes, which is most important for better accuracy.

Acknowledgments

The author thanks Tefal Company for its financial and technical support and the Center of Medical Imaging of Compiegne for his DXA access. He also thanks the Algerian government for Doctorate scholarships of S. Bousbiat, I. Assadi and E Dongmo. He also thanks his doctoral students: C Legallais, H Morel, M Fenech, MV Moreno, R Kieffer and M Maasrani for their important scientific contributions.

8 References

1. Bray GA. Medical consequences of obesity. Journal of Clinical Endocrinology and Metabolism. 2004, 89:2583–2589.
2. MY Jaffrin. Body composition determination by bioimpedance: an update. Current Opinion in clinical nutrition and metabolic care, 12 (2009) 482–486.
3. UG Kyle, I Bosaeus, AD De Lorenzo, P Deurenberg, M Elia, JM Gomez, BL Heitmann, et al Bioelectrical impedance analysis-part II: utilization in clinical practice. Clinical Nutrition 23(2004) 1430–1453.
4. EC Rush, V Chandu, LD Plank. Prediction of fat-free mass by bioimpedance analysis in migrant Asian Indian men and women: a cross validation study. Int J of Obesity30 (2006) 1125–1131.
5. DS Bhat, CS Yajnik, MG Sayyad, KN Raut, HG Lubree, SS Rege et al. Body fat measurement in Indian men: comparison of three methods based on a two compartment model. Int J Obes Relat Metab Disord 29(2005) 842–848.
6. P Duremberg, K Van der Kooy, R Leenen, JA Westrate,Seidel JC. Sex and age specific prediction formulas for estimating body composition from bioelectrical impedance: a cross-validation study. Int J Obes Relat Metab Disord 15(1991) 17–25.
7. MY Jaffrin, R Kieffer, MV Moreno. Evaluation of a foot-to-foot impedance meter measuring extracellular fluid volume in addition to fat-free-mass and fat tissue mass. Nutrition 21 (2005) 815–824.
8. T Hanai. Electrical properties of emulsions. In D Sherman, editor. Emulsions science. London: academic press; 1968:354–477.
9. MY Jaffrin, MV Moreno. Measurements of total body water with a foot-to-foot impedance meter. Med Eng & Physics 30 (2008) 483–489.
10. JR Matthie. Second generation mixture theory equation for estimating intracellular water using bioimpedance spectroscopy. J Appl Physiol 99 (2005) 780–791.
11. MV Moreno, D.D Djeddi, MY Jaffrin. Assessment of body composition in adolescent subjects with anorexia nervosa by bioimpedance. Med Eng & Physics 30 (2008)783–791.
12. MY Jaffrin, H Morel. Body fluid volumes measurements by impedance: A review of bioimpedance spectroscopy (BIS) and bioimpedance analysis (BIA) methods. Med Eng & Physics. 30 (2008) 1257–1269.
13. MY Jaffrin M Fenech, MV Moreno, R Kieffer. Total body water measurement by a modification of the bioimpedance spectroscopy method. Med Bio Eng Comput 44 (2006) 873–882.
14. G P Pichler, O Amouzadeh-Ghadikolai, A Lesis, F Skrabal. A critical analysis of whole body bioimpedance spectroscopy (BIS) for the estimation of body compartment in health and disease. Med Eng &Physics. 35 (2013) 616–625.
15. L Parker, JJ Reilly, C Slater, JCK Wells, Y Pitsiladis. Validity of six field and laboratory methods for measurement of body composition in boys. Obesity Research 11 (2003) 852–858.

16. SA Jebb, M Servio, PR Murgatroyd, S Evans, G, Frühbeck, AM Prentice. Validity of the leg-to-leg bioimpedance to estimate changes in body fat during weight loss and regain in overweight women: a comparison with multi-compartment models. Intern J of Obesity 31 (2000) 756–762.
17. HC Lukaski, WA Siders. Validity and accuracy of regional bioelectrical impedance devices to determine whole-body fatness. Nutrition19 (2003) 851–857.
18. AC Utter, DC Nieman, AN Ward, DE Butterworth. Use of leg-to-leg bioelectrical impedance method in assessing body-composition change in obese women. Am J Clin Nutr 6 (1999)603–607.
19. J Hosking, BS Metcalf, AN Jeffery, LD Voss, TJ Wilkin. Validation of foot-to-foot bioelectrical impedance analysis with Dual X-Ray absorptiometry in the assessment of body composition in young children: the early bird cohort. Brit J of Nutrition 96 (2006) 1163–1168.
20. AM Swartz, MJ Evans, GA King, and DL Thompson. Evaluation of foot-to-foot bioelectrical impedance analyser in highly active and less active young men. Brit J of Nutr 88 (2002)205–210.
21. D Radley, CB Cooke,NJ Fuller, B Oldroyd, JG Truscott, WA Coward et al. Validity of foot-to-foot bio-electrical impedance analysis body composition estimates in overweight and obese children. Int J Body Compos Res 7 (2009) 15–20.
22. A Boulier, WC Chumlea, A De Lorenzo, P Deurenberg, SS Guo, L Leger, et al.Body composition estimation using leg-to-leg bioelectrical impedance: a six-site international cross validation study. Intern J of Body Composition Res.3 (2005) 31–39.

23. S Demura, S Sato, T Kitabayashi. Percentage of total body fat as estimated by three automatic bioelectrical impedance analyzers. J Physiol Anthropol Appl Human Sci 23 (2004) 93–94.
24. E Volgyi, FA Tylavsky, A Lyytikainen, H Suominen, M Alen, SCheng. Assessing body composition with DXA and bioimpedance:effects of obesity, physical activity and age. Obesity 16 (2008) 700–705.
25. JS Lim, JS Hwang, JA Lee, DH Kim, KD Park, JS Jeong, GJ Cheon. Cross calibration of multi-frequency bioelectrical impedance analysis with eight-point tactile electrodes and DXA for assessment of body composition in healthy children aged 6–18 years. Pediatric Intern51 (2009) 263–268.
26. KJ Shafer, WA Siders, LK Johnson, HC Lukaski. Validity of segmental multiple-frequency bioelectrical impedance analysis to estimate body composition of adults across a range of body mass indexes. Nutrition 25 (2009) 25–32.
27. N Neovius, J, Udden, E. Hemmington. Assessment of change in body fat percentage with DXA and eight-electrode BIA in centrally obese women. Med Sci in Sports and Exerc 39 (2007) 1299–1303.
28. S Bousbiat, MY Jaffrin, E Dongmo. Comparison of body fat-free masses calculated from hand to foot and foot-to-foot resistances with DXA measurements. Med Biol Eng Comput 49 (2011) 1329–1336
29. HC Lukaski. Validation of body composition techniques in the dialysis population. ASAIO J 43(1997):251–255
30. S Sato, S Demura, T Kitabayashi, T Nogushi. Segmental study composition assessment for obese Japanese adults by single frequency bioelectrical impedance analysis with 8-point contact electrodes. J Physiol Anthropol 26 (2007) 535–540.
31. D Pietrobelli, F Rubiano, MP St Onge, SB Heymsfield. New bioimpedance analysis system: improved phenotyping with whole-body analysis. Eur J Clin Nutr 58 (2004)1479–1484.
32. CHY Ling, AJM De Craen, PE Slagboom, DA Gunn, MPM Stokkel, RGJ Westendor et al. Accuracy of direct segmental multi-frequency bioimpedance analysis in the assessment of total body and segmental body composition in middle-aged adult population. Clin Nutr. 30 (2011) 610–615.
33. AL Gibson, JC Holmes, RL Desautels, LB Edmonds,L Nuudi. Ability of new octapolar bioimpedance spectroscopy analysers to predict 4-component model percentage body fat in Hispanic, black and white adults. Am J Clin Nutr. 87 (2008) 332–338.
34. LW Organ, GB Bradham, D T Gore and SL Lozier. Segmental bioelectrical impedance analysis: theory and application of a new technique. J Appl Physiol 77(1) (1994) 98–112.
35. MY Jaffrin, H Morel. Measurements of body composition in limbs and trunk using a eight contact electrodes impedance meter. Med Eng & Phys 31 (2009) 1079–1086.
36. MY Jaffrin, H Morel. Extracellular volume measurements using bioimpedance spectroscopy-Hanai method and wrist-ankle resistance at 50 kHz. Med Biol Eng Comput. 47 (2009) 77–84.

37. Z Wang, W Shen, DP Kotler, S Heshka et al. Total body protein: a new cellular level mass and distribution prediction model. Am J Clin Nutrition 78 (2003): 979–984.
38. A De Lorenzo, A Andreoli, A Matthie, PO Withers. Predicting cell mass with bioimpedance by using theoretical methods: a technological review. J Appl Physiol 82(5) (1997) 1542–1558.
39. G Sergi, M Bussolotto, P Perini, I Calliari et al. Accuracy of bioelectrical bioimpedance analysis for the assessment of extracellular space in healthy subjects and in fluid retention states. Ann Nutr Metab 38 (1994) 158–165.
40. MY Jaffrin, S Bousbiat, E Dongmo. A comparison between two methods for measuring limb resistances with wrist and ankle resistances. Med Eng & Phys. 33 (2011) 943–949 38.
41. H Morel, MY Jaffrin. A bridge from bioimpedance spectroscopy to 50 kHz bioimpedance analysis: application total body water measurements. Physiol Meas 29 (2008) S465–S478.
42. S Bousbiat, MY Jaffrin, I Assadi. Factors influencing accuracy and reproducibility of body resistance measurements by foot-to-foot impedance meters. Med Eng & Technol 39 (2014) 35–43.
43. MY Jaffrin, S Bousbiat. Accuracy of plantar electrodes compared with hand and foot electrodes in fat-free-mass measurement. J of Health Care Eng. 5(2) (2014) 123–144.

Nomenclature

H	body height, m
R_{13}	hand-to-foot resistance, Ω
R_{34}	foot-to-foot resistance, Ω
Re	extracellular resistance Ω
Ri	intracellular resistance
Scc	contact area of current electrode with foot, cm^2
Scv	contact area of voltage electrode with foot, cm^2
Ve	extracellular volume, L
Ve_t	extracellular volume by Tefal
V_{tx}	extracellular volume by Xitron
V_i	intracellular volume, L
W	body weight, kg
Z	impedance, Ω
Z_{50}	impedance at 50 kHz, Ω

Abbreviations

BIS	biompedance spectroscopy
BMC	bone mineral content, kg
BMI	body mass index, $kg\text{-}m^{-2}$
DXA	Dual X-ray absorptiometer

ECW extracellular water volume, L
FFI foot-to-foot impedance meter
FM fat tissue mass, kg
FMd fat tissue mass by DXA
FMi fat tissue mass by impedance
FFM fat-free-mass, kg
FFMd FFM measured by DXA, kg
FFMi FFM measured by impedance, kg
FFMt FFM measured by Tefal
LBM lean body mass, kg
SD Standard deviation
TBW total body water, L

Greek

ρ resistivity, ohm-cm
Ω resistance ohm
Subscript i: impedance, d: DXA